S100 22 and 23

THE OPEN UNIVERSITY

Science Foundation Course Units 22 and 23

The Earth, Its Shape, Internal Structure and Composition / The Earth's Magnetic Field

The Open University

Science Foundation Course Unit 23

THE EARTH'S MAGNETIC FIELD

Prepared by the Science Foundation Course Team

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Contents

	Conceptual Diagram	4
	List of Scientific Terms, Concepts and Principles	5
	Objectives	6
23.1	**The Earth and its Energy**	7
23.2	**The Nature and Properties of Magnetism**	8
23.2.1	Permanent magnets	8
23.2.2	Magnetic forces and fields	8
23.2.3	The dipole field	11
23.3	**The Earth's Magnetic Field**	14
23.3.1	The antiquity of geomagnetic studies	14
23.3.2	The magnetic elements	14
23.3.3	What is the Earth's field like now?	17
23.3.4	How has the geomagnetic field changed?	20
23.3.5	Indirect measurement of the past geomagnetic field	23
23.3.6	How old is the geomagnetic field?	24
23.3.7	Has the geomagnetic field always been mainly dipolar?	24
23.3.8	Changes in the geomagnetic induction	26
23.3.9	Field reversals: an unexpected bonus	27
23.4	**The Origin of the Geomagnetic Field**	29
23.4.1	Introduction	29
23.4.2	Permanent magnetism	29
23.4.3	Rotation of a massive body	29
23.4.4	The geomagnetic dynamo	30
23.5	**Summary**	32
	Reading List	33
	Appendix 1 (White) Glossary	33
	Appendix 2 (Black) Angular dependence of magnetic force	34
	Appendix 3 (Black) Induction from a magnetic dipole	35
	Appendix 4 (Black) Relationships between the magnetic elements	36
	Appendix 5 (Black) Calculation of geomagnetic or palaeomagnetic pole positions	36
	Self-Assessment Questions	37
	Self-Assessment Answers and Comments	41

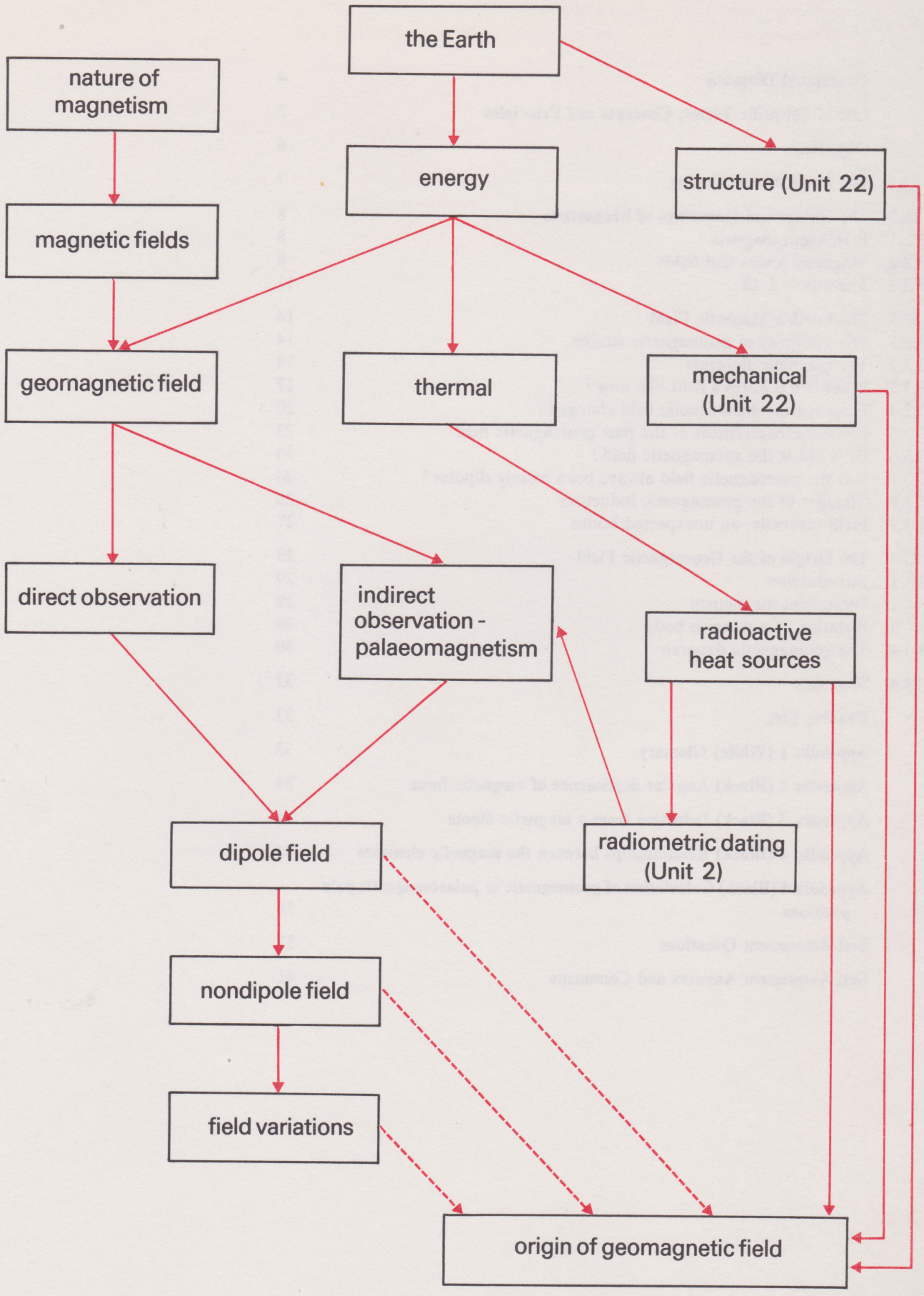

the Earth
nature of magnetism
energy
structure (Unit 22)
magnetic fields
geomagnetic field
thermal
mechanical (Unit 22)
direct observation
indirect observation - palaeomagnetism
radioactive heat sources
dipole field
radiometric dating (Unit 2)
nondipole field
field variations
origin of geomagnetic field

Table A List of Scientific Terms, Concepts and Principles used in Unit 23

Taken as pre-requisites			Introduced in this Unit			
1 Assumed from general knowledge	2 Introduced in a previous Unit	Unit No.	3 Developed in this Unit	Page No.	4 Developed in a later Unit	Unit No.
magnet	radiometric dating	2, 6	law of magnetic attraction and repulsion	8		
magnetic compass	electron	4	magnetic force	8		
contour lines	nucleus	4	magnetic poles	8		
latitude	conductor	4	permanent magnetism	8		
longitude	current	4	lines of induction	9		
geographic east	electric field	4	magnetic field	9		
geographic north	lines of force	4	magnetic induction	9		
	ammeter	4	magnetic interaction	9		
	electric charge	4	permeability	10		
	linear velocity	3	relative permeability	10		
	precession	22	dipole field	11		
			magnetic dipole	11		
			solenoid	11		
			equatorial axis	12		
			principal axis	12		
			Earth's magnetic field	14		
			geomagnetic field	14		
			geomagnetic induction	14		
			declination	15		
			inclination	15		
			magnetic elements	15		
			magnetic meridian	15		
			isoclinics	17		
			isogonic charts	17		
			isogonic lines / isogonics	17		
			isomagnetic charts	17		
			axial dipole	18		
			geocentric	18		
			geomagnetic dipole	18		
			geomagnetic poles	18		
			geomagnetic equator	19		
			magnetic dip poles	19		
			non-dipole field	19		
			secular variation	20		
			palaeomagnetism	23		
			palaeomagnetic pole position	24		
			field reversal	27		
			self-reversal	27		
			Curie temperature / Curie point	29		
			geomagnetic dynamo	30		
			dynamo	31		
			induced current	31		
			self-exciting dynamo	31		
				Section No.		
			MAFS			
			resolution	4D		
			vector	4D		
			HED			
			henry	3.1.3		
			tesla	3.1.3		

Scientific terms used in this Unit but not listed above are marked thus † and defined in the glossary (p. 33).

Objectives

When you have completed your study of this Unit, you should be able to:

1 Define in your own words, recognize valid definitions of, or use in correct context, the terms, concepts and principles in column 3 of Table A.

2 State the simple conspicuous properties of the magnet.

3 Illustrate diagrammatically the shapes of the magnetic fields produced by (i) a straight current-carrying conductor, and (ii) a dipole.

4 Perform simple calculations involving (i) the magnetic interaction between two straight, parallel current-carrying conductors, and (ii) the magnetic fields along the principal and equatorial axes of a dipole.

5 State very briefly the fundamental origin of the magnetic fields produced by permanent magnets and current-carrying conductors.

6 Illustrate diagrammatically the definitions of the magnetic elements and recognize the truth or falsity of statements derived from these definitions.

7 Describe the main features of the Earth's present magnetic field.

8 Distinguish between, and recognize, the properties of isomagnetic charts for different magnetic elements.

9 Describe (in words and diagrammatically) how the Earth's dipole and non-dipole fields have changed over the period covered by direct field observation.

10 Describe (in words and diagrammatically) the main changes in the geomagnetic field as deduced from measurements on rocks and artefacts.

11 Describe briefly two simple theories for the origin of the Earth's magnetic field and indicate why they are not valid.

12 Explain the basic physical principles underlying the dynamo theory for the origin of the Earth's magnetic field.

23.1 The Earth and its Energy

In Unit 22 you spent most of your time examining how Earth scientists have built up a picture of the Earth's gross structure. In particular, you saw how the Earth comprises a comparatively thin outer crust, a mantle which accounts for over 80 per cent of the Earth's volume and a core which is in two parts, the outer one liquid and the inner one solid. This overall structure was determined by analysing the behaviour of earthquake waves as they pass through the Earth. In other words, a part of the Earth's own energy was used to infer something about the Earth itself.

But the energy released by earthquakes, volcanic activity and similar processes is not the only, nor quantitatively the most important, form of energy in the Earth—although its effects may be the most spectacular. The most impressive terrestrial phenomenon from the energy point of view is the production of heat, for each year over 8×10^{20} joules of heat move upwards from the Earth's interior and escape from the surface. The energy involved here is many orders of magnitude greater than that involved in all other Earth processes put together.

Heat plays an important role in almost all theories about the origin and development of every part of the Earth. The Earth's magnetic field —which itself contains energy—is no exception, for it is probably produced as a result of thermal processes in the liquid outer core. However, historically, and with good reason, the study of the Earth's magnetic field has been primarily observational. The existence of the field was appreciated long before anyone had the faintest idea how it was produced; in fact, the only viable theory for the origin of the field has been developed within the past twenty years.

In this Unit we shall, first, summarize the directly observed characteristics of the Earth's magnetic field—what the field is like now, how it is changing, and how it has changed over the 130 years or so during which its behaviour has been measured systematically. We shall then examine how the magnetism of rocks may be used to extend the observation of the field backwards in time for hundreds of millions of years. When we have collected together the important properties of the field, we shall take a brief look at theories for the origin of the field. Before we can begin to think about the Earth's magnetism, however, we must first examine the nature of magnetism itself.

23.2 The Nature and Properties of Magnetism

23.2.1 Permanent magnets

Almost everyone is familiar with the magnet in one form or another because it appears so frequently in everyday life. The magnetic compass, magnetic chessmen, children's games such as those in which little steel 'fishes' are picked up with a 'fishing rod' comprising a magnet on the end of a string, and some self-fastening doors on refrigerators and radio cabinets, are just a few of the many examples. Some materials, such as steel, become magnetic even though they were never intended to be. If you try lifting a small steel paper clip on the tip of a screwdriver or penknife, the chances are that you will succeed! All these magnets are termed *permanent magnets* because they retain their magnetism almost indefinitely. The chemical elements from which permanent magnets can be made are iron, nickel and cobalt, although most modern magnets are made from alloys usually containing one or more of these elements.

permanent magnets

Some of the properties of a magnet are extremely conspicuous, among them the following:

(i) A magnet will attract small pieces of iron and steel which adhere to it. This is most marked in regions near the ends of the magnet, called the *magnetic poles*, or simply *poles*.

magnetic poles

(ii) If suspended horizontally so that it can rotate freely about a vertical axis (an example is the magnetic compass), a bar magnet will come to rest in a direction which is roughly north-south. The end pointing roughly towards the north geographic pole of the Earth is called the *north pole*, or *N pole*, of the magnet; and the end pointing roughly towards the south geographic pole is called the *south pole*, or *S pole*, of the magnet.

north pole
south pole

(iii) A second magnet brought near the first experiences a mechanical force. If the N pole of one magnet is brought near the S pole of the other, the magnets will attract each other. On the other hand, if the N pole of one magnet is brought near the N pole of the other, or the S pole of one near the S pole of the other, they will repel. Thus there is a fundamental law of magnetic attraction and repulsion, which is that *like poles repel and unlike poles attract each other.*

law of magnetic attraction and repulsion

However, simple and interesting though these properties be, they give few clues to the fundamental nature of magnetism. A permanent magnet looks deceptively simple from the outside; but internally it is a very complicated device which depends on the interactions of many atoms in close proximity.

23.2.2 Magnetic forces and fields

You will recall that in Unit 4 and the corresponding TV programme we saw that two parallel conductors, each carrying an electric current, exert a force on each other (Fig. 1). If the two currents are in the same direction, the force is one of attraction; but if the currents are opposed, the force is one of repulsion.

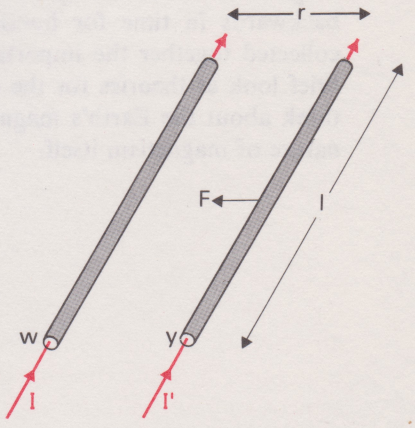


Figure 1 Two parallel conductors carrying currents I *and* I′ *respectively, exert a mutual force. If* I *and* I′ *are in the same direction the force is one of attraction; but if* I *and* I′ *are opposite, the force is one of repulsion. If Y is regarded as the test wire to measure the force* (F) *and hence the magnetic induction* (B) *produced by W, then if* I′ = 1 *A and* l = 1 *m,* B = F. *In other words, the force on Y is equal to the magnetic induction at distance* r *from W.*

Do you remember how this force is produced?

The current in each conductor 'produces' a magnetic field which interacts with the other current-carrying conductor to give a mutual force.

However, it is observed experimentally that if the current in one of the wires is switched off, the force disappears. This illustrates an important characteristic of the magnetic interaction between electric charges, namely, that it is only observed when *both* sets of charges are moving with respect to the observer—that is, when both currents are flowing. But this raises an awkward question. If only one of the two parallel wires carries a current, does that current still produce a magnetic field? Strictly speaking this question cannot be answered because the only way in which a magnetic field can be detected is by using it to produce a magnetic interaction—and this can be done only if the second wire also carries a current, or moving charge. However, although the existence of a magnetic field in the vicinity of a single set of moving charges cannot be proved, it is usual to *infer* that such a field does, in fact, exist. Thus it is conventional to say that a magnetic field is 'produced' whenever an electric charge is moving with respect to the observer.

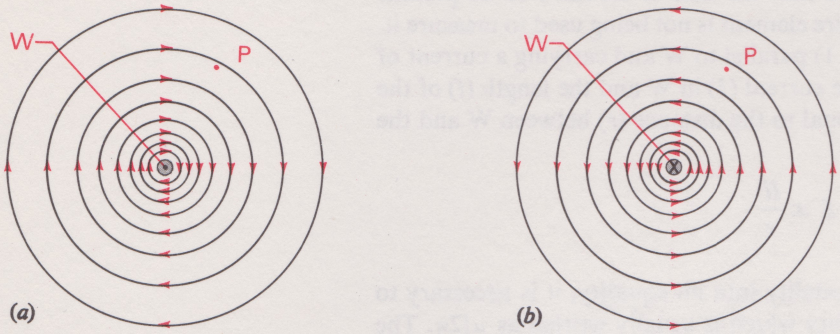


Figure 2 The lines of induction around a straight current-carrying conductor, W. In (a) the direction of the current is upward out of the paper (⊙); in (b) the current direction is downward into the paper (⊗).

The basic quantity associated with the magnetic field, which defines its magnitude and direction, is termed the *magnetic induction*, ***B***. This is similar in spirit to, but somewhat more complex than, the quantity E used in Unit 4 to define the electric field, the field produced by a stationary electric charge. Just as electric fields may be represented by lines of force, magnetic fields may be represented by *lines of induction*. However, for historical reasons, lines of electric force and lines of magnetic induction are drawn in different ways. Lines of force, you will recall from Unit 4, are drawn radially from an electric charge, and a small test charge free to move in the electric field will move along a line of force. Lines of induction, on the other hand, are drawn in such a way that a small compass needle placed in a magnetic field will come to rest tangentially to one of them. Thus, for a single current-carrying wire, the lines of induction form a series of concentric rings centred on the wire (Fig. 2). The arrows are drawn in the direction in which the N pole of the compass needle would point. The direction of the test compass needle in any given case is, of course, an experimental result; but for a single current-carrying conductor a convenient way of remembering the direction is to note that the arrows are drawn in such a sense that a right-handed screw rotated in this sense would advance in the direction of the current flow.

magnetic induction

lines of induction

In the experiment with two parallel current-carrying conductors, at what angle to the lines of induction does the mutual force cause the conductors to move?

The force between two parallel current-carrying conductors causes them to move together when the currents are in the same direction and apart

when the currents are in opposite directions. If you visualize the concentric lines of induction around each conductor as the conductors move with respect to each other, you should be able to deduce that the movement is perpendicular to the lines.

In principle, the magnetic induction, B, is defined quantitatively in a similar way to the electric field strength, E, but taking into account the difference that E refers to a field produced by a static charge whereas B refers to a field produced by moving charge. For example, the magnetic induction at a point close to a single straight current-carrying wire, W (Fig. 2), is defined as the 'would-be force per metre of wire carrying a current of one ampere when placed parallel to W'.

Do you recall why the words 'would-be' are introduced into this definition?

By analogy with the definition of an electric field (Unit 4), the words 'would-be' are used to emphasize that the field is assumed to be present even when the current-carrying wire element is not being used to measure it. The force (F) on a test wire (Fig. 1) parallel to W and carrying a current of one ampere is proportional to the current (I) in W and the length (l) of the test wire, and inversely proportional to the distance (r) between W and the test wire, that is:

$$F \propto \frac{Il}{r}$$

In order to change this proportionality into an equality, it is necessary to insert a constant of proportionality which is usually written as $\mu/2\pi$. The expression for the force then becomes:

$$F = \frac{\mu Il}{2\pi r} \text{ newton}$$

The 2π factor is introduced mainly because it makes the notation more rational in more sophisticated problems. The μ factor indicates that the force between the conductors also depends on the medium separating them. μ is a constant for any given medium, known as its *permeability*. It is usually written in the form $\mu = \mu_r\mu_0$ where μ_0 is the permeability of a vacuum and μ_r is the *relative permeability* of the medium, that is, the permeability relative to that for vacuum. For air, μ_r is very close to unity; and so for most purposes μ_0 may be used for air as well as a vacuum. In this Unit, we shall only be concerned with magnetic fields in air and thus will use μ_0 throughout. The force between two parallel wires in air then becomes:

permeability

relative permeability

$$F = \frac{\mu_0 Il}{2\pi r} \text{ newton}$$

The magnetic induction at the position of the test wire ('the would-be force per metre of wire carrying a current of one ampere when placed parallel to W') is then obtained from this equation by putting $l = 1$ (that is, for a test wire one metre long). So:

$$F = B = \frac{\mu_0 I}{2\pi r}$$

The unit of B is weber metre $^{-2}$ (Wb m^{-2}), which is given the special name, *tesla* (T). If you are unsure about the nature of these units, or if you feel you need further information about them, you should consult section 3 of *HED*.

tesla

Problem: **The magnetic induction 3.5 m away from a straight wire carrying a current of 10.5 A is found to be 6×10^{-7} T in air.**

Calculate μ_0.

Solution: The magnetic induction at distance r from a straight wire with a current I is given by

$$B = \frac{\mu_0 I}{2\pi r}$$

Re-arranging, to calculate μ_0:

$$\mu_0 = \frac{2\pi r B}{I}$$

For this problem:

$$\mu_0 = \frac{2\pi \times 3.5 \times 6 \times 10^{-7}}{10.5}$$

$$= 4\pi 10^{-7} \text{ numerically.}$$

The unit of B is T (= Wb m^{-2}), the unit of r is m and the unit of I is A. The unit of μ_0 is thus

$$\left(\frac{rB}{I}\right) \rightarrow \frac{\text{m.Wb m}^{-2}}{\text{A}} = \text{Wb m}^{-1}\text{ A}^{-1}$$

The unit Wb A^{-1} is given a special name, *henry* (H). Thus,

$$\mu_0 = 4\pi 10^{-7} \text{ H m}^{-1}$$

The theory given above for the magnetic interaction between two straight current-carrying conductors is only valid if the conductors are parallel. When the conductors are not parallel the situation is more complicated. This is discussed briefly in Appendix 2 (Black).

23.2.3 The dipole field

The magnetic field produced by a straight wire carrying a current is the simplest known field but is not, in practice, the most important. This distinction must go to the field produced by a *solenoid*, a long current-carrying wire wound into the form of a helical† coil. The field produced by a loosely wound solenoid is shown in Figure 3. For points close to the wire itself an observer is not aware that the wire is bent. The wire behaves magnetically almost as if it were straight, the lines of induction being concentric circles. But away from the immediate vicinity of the wire the field is the vector sum (see *MAFS*, section 4) of the fields set up by all the turns that make up the solenoid.

In a tightly wound solenoid—one with no gaps between the turns—the lines of induction close to each turn of the wire tend to cancel with those from adjacent turns, producing the net field shown in Figure 4. A field of this shape is known as a *dipole field*, and the solenoid is said to act as a *magnetic dipole*, or simply *dipole*. The reason for the name 'dipole' will become apparent a little later.

dipole field
magnetic dipole

How could the magnetic induction at any point in a dipole field be measured?

The magnetic induction at a point in the dipole field may be determined, in principle, in the same way as that of a field produced by a long straight wire—by measuring the force exerted on a current-carrying element (test wire) placed in the field. The general expression for the magnetic induction at any point in a dipole field is complicated (see black-page Appendix 3).

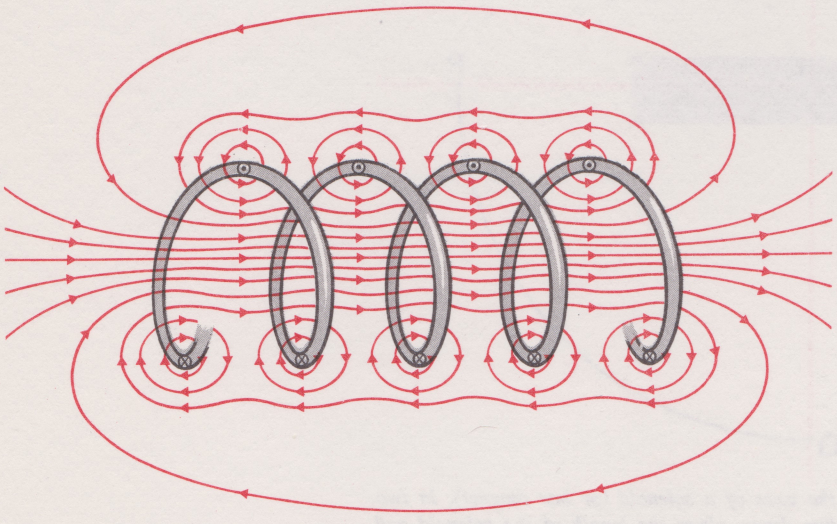


Figure 3 Lines of induction for the magnetic field produced by a loosely-wound solenoid. The convention for the current direction in the wire is the same as that in Figure 2.

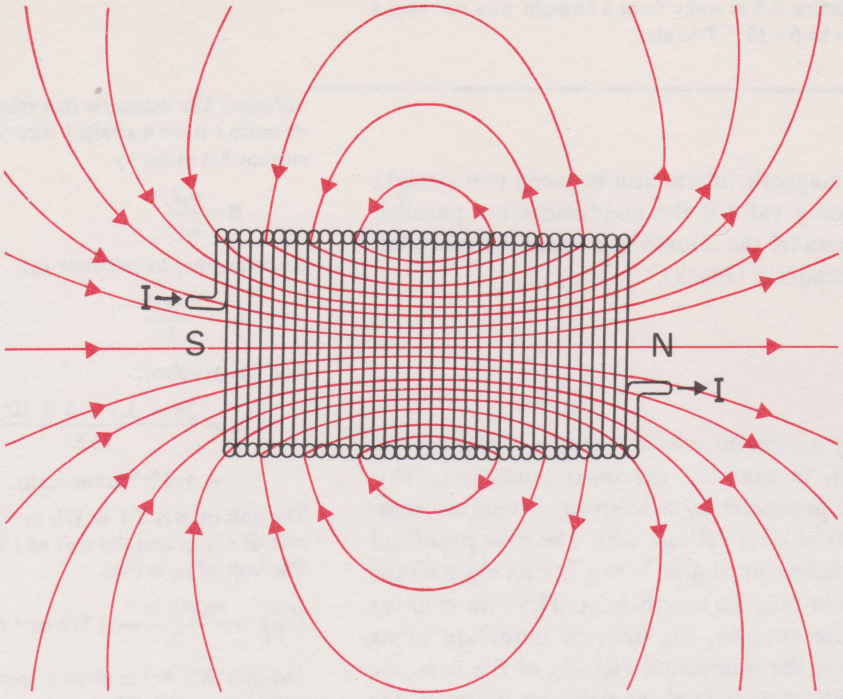


Figure 4 Lines of induction for the magnetic field produced by a tightly wound solenoid.

However, there is one simple feature of this field which is worth remembering: that at a given distance from the centre of a solenoid and outside it, the magnetic induction at a point on the principal axis is exactly twice the magnetic induction at a point on an equatorial axis. This important feature is explained in greater detail in the caption to Figure 5.

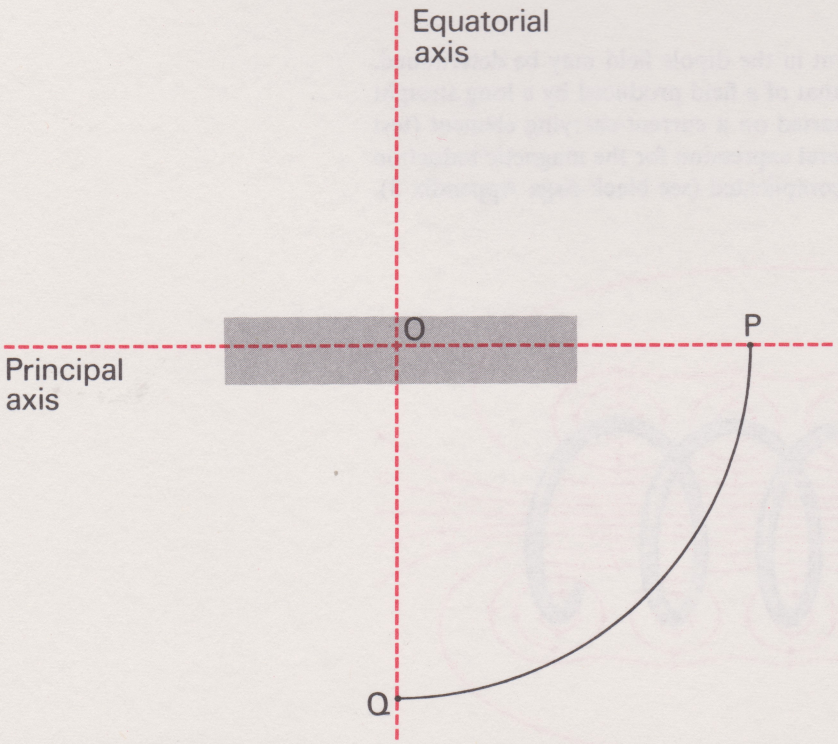


Figure 5 The magnetic induction on the axes of a solenoid (or bar magnet), in two dimensions. The principal axis *is the line drawn along the length of the solenoid and through its centre, O. An* equatorial axis *is a line drawn through the centre of the solenoid at right angles to the principal axis. At P the magnetic induction is exactly twice that at Q. OP = OQ.*

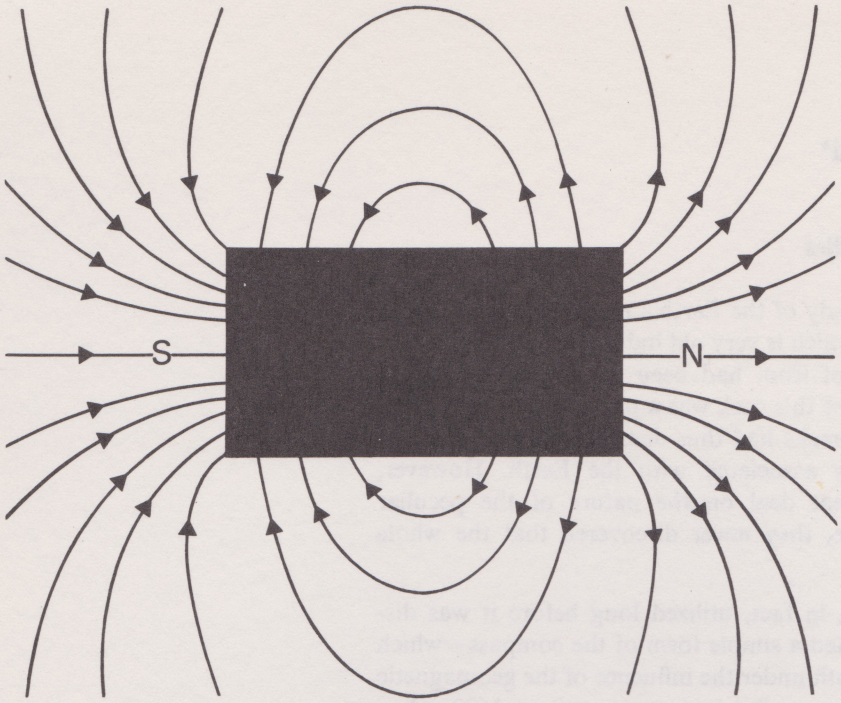


Figure 6 Lines of induction for the magnetic field produced by a bar magnet.

The reason for the use of the term 'dipole' in connection with the field produced by a solenoid becomes apparent when we compare this field with that produced by a bar magnet (Fig. 6). It is found experimentally that outside the respective bodies the magnetic fields have identical shape. Furthermore, many of the properties of a bar magnet and a solenoid are also similar. The simple properties of the bar magnet described in section 23.2.1, for example, are shared by the solenoid. In particular, the solenoid acts as though it possessed polarity, a N pole at one end and a S pole at the other (Fig. 4). Historically, the concept of 'poles' was applied to the bar magnet long before the solenoid was invented. The term 'dipole', which simply means 'two poles', thus came to be used to describe the field produced by a bar magnet and then, later, by extension, the identical field produced by the solenoid.

The similarity of the magnetic fields set up by the bar magnet and solenoid also suggests a similar origin of the fields. The solenoid field is, of course, a consequence of the motion of the electric charges (the electrons) in the wire. From this it is possible to infer that the magnetic field from a permanent magnet is also likely to be due to the movement of electrons. Needless to say, the behaviour of charged particles which will produce spontaneously, from a solid body, a field identical to that produced by the artificially induced and comparatively simple electric current in a wire, must be extremely complex. The permanent magnet is so common that most people have become blasé about it. Yet the degree of spontaneous ordering inherent in a permanent magnet is really quite amazing.

23.3 The Earth's Magnetic Field*

23.3.1 The antiquity of geomagnetic studies

There is a sense in which the study of the Earth's magnetism is as old as the study of the magnet itself—which is very old indeed. Lodestone, a very strongly magnetic natural ore of iron, had been discovered in ancient Greece by at least 600 BC. Because this rock was a part, albeit a very small part, of the Earth's crust, the Greeks had thus demonstrated for the first time that magnetism is closely associated with the Earth. However, although they speculated a great deal on the nature of the peculiar attractive property of lodestone, they never discovered that the whole Earth acts as a magnet.

The Earth's magnetic field was, in fact, utilized long before it was discovered. The Chinese had invented a simple form of the compass—which pointed approximately north-south under the influence of the geomagnetic field—by at least the first century AD. But it was not until AD 1600, when William Gilbert, a London physician, showed that the behaviour of a compass needle at the Earth's surface was very similar to that of an iron needle placed on the surface of a lodestone sphere, that people began to realize that magnetism is a fundamental property of the Earth.

Serious and systematic measurements of the Earth's magnetic field were only begun during the early nineteenth century, less than 200 years ago. Thus all our *direct* knowledge of the geomagnetic field has been acquired over a period which represents less than 0.000005 per cent (or 0.00005 per cent if we take account of the Chinese compass) of the age of the Earth! However, beggars have no choice—and we must rest content with but a few hundred years. What, then, has direct observation told us about the geomagnetic field over that period of time?

In this section we have tacitly assumed that the Earth has a magnetic field to observe. What simple fact already stated (excluding Gilbert's work) makes this assumption warranted?

The fact that the compass needle always points approximately north-south whatever its location (23.2.1) suggests that the needle is being aligned by more than a purely local magnetic field. A field which has this effect all over the Earth's surface can only be produced by the Earth itself.

23.3.2 The magnetic elements

Study comment

There are quite a few definitions in this short section. Having to memorize them is rather tedious, but is essential if you are to understand the features of the geomagnetic field. You would be well advised to spend a little time upon them now to avoid confusion later on, for the magnetic elements are the basic notation used to describe the Earth's magnetic field.

Before any sense can be made of the magnetic field at the Earth's surface, it is first necessary to define a common frame of reference to ensure that data from all over the world are strictly comparable. In theory there are many ways in which this could be done; but in practice it is usual to measure the Earth's magnetic induction (or the *geomagnetic induction*) with respect to three axes at right angles (Fig. 7)—geographic north, geographic east and the vertical (that is, the vertical down from the Earth's surface to its centre).

geomagnetic induction

* *The Earth's magnetic field is often referred to as the* geomagnetic field.

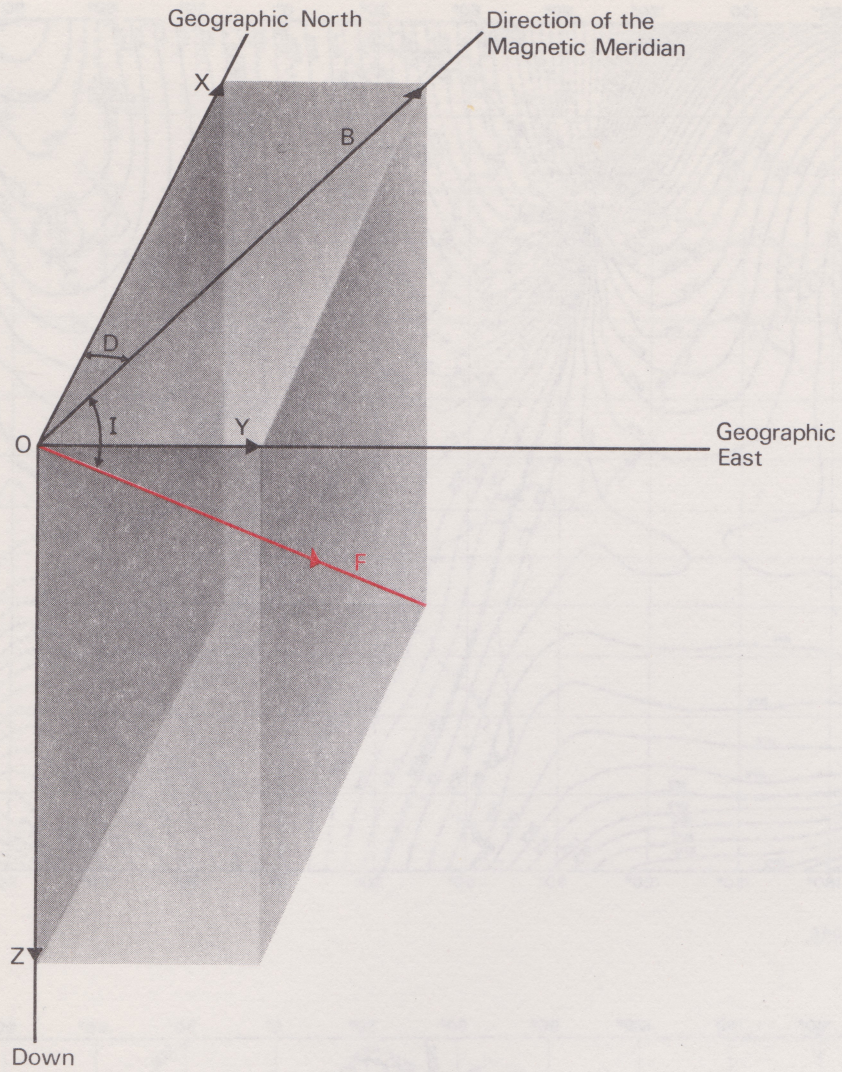


Figure 7 The magnetic elements.

Suppose that the geomagnetic induction at any point 0 on the Earth's surface is F, where, in general, F will lie at some unknown angle to the frame of reference. F is a vector—which is to say, it has both a magnitude and a direction (see *MAFS*, section 4). In Figure 7, the line marked F is thus in the direction of the geomagnetic induction at 0 and its length is proportional to the magnitude of the geomagnetic induction.

A compass needle at 0, free to rotate in the horizontal plane, will come to rest along B, the horizontal component of F. The angle that B makes with geographic (true) north is called the *declination*, D, and is measured east of true north (ETN). The vertical plane through F and B is called the *magnetic meridian* at the site 0. The vertical plane through the geographic north direction is, of course, the *geographic meridian*; and so D is also the angle between the geographic and magnetic meridians at 0.

declination

magnetic meridian
geographic meridian

The angle that F makes with the horizontal is called the *inclination*, I. I is regarded as positive if F lies below the horizontal and negative if F lies above the horizontal.

inclination

F may also be regarded as the vector sum (see *MAFS*, section 4) of three components at right angles—X along true north, Y along geographic east and Z along the vertical. X, Y and Z are regarded as positive if in the directions shown in Figure 7, and negative if in the opposite directions. In Figure 7 the lengths of X, Y and Z are proportional to their magnitudes.

X, Y, Z, B, F, D and I are known as the *magnetic elements*. Trigonometric relationships between the magnetic elements are given in Appendix 4 (Black).

magnetic elements

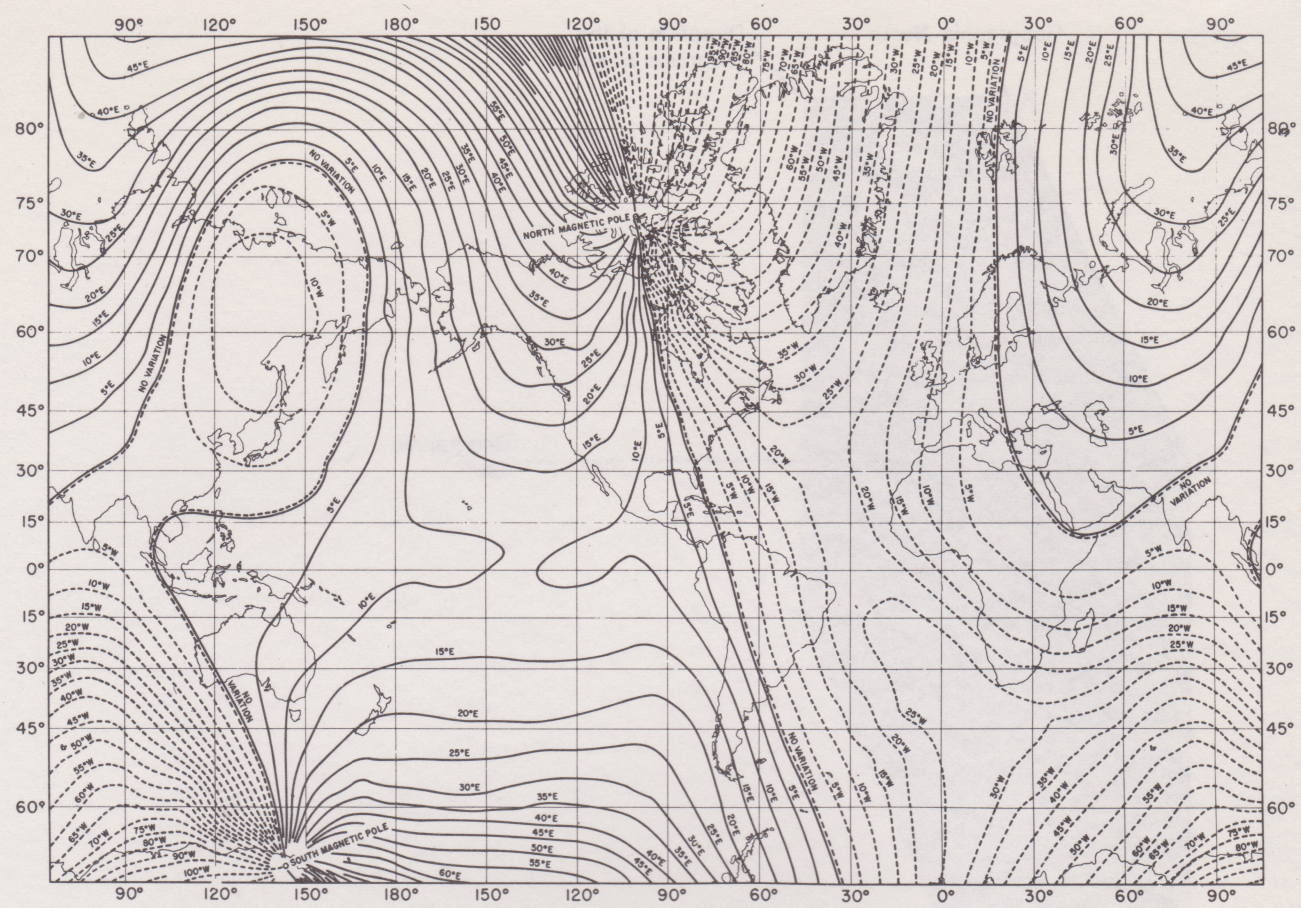


Figure 8 Isogonic chart for the year 1955.

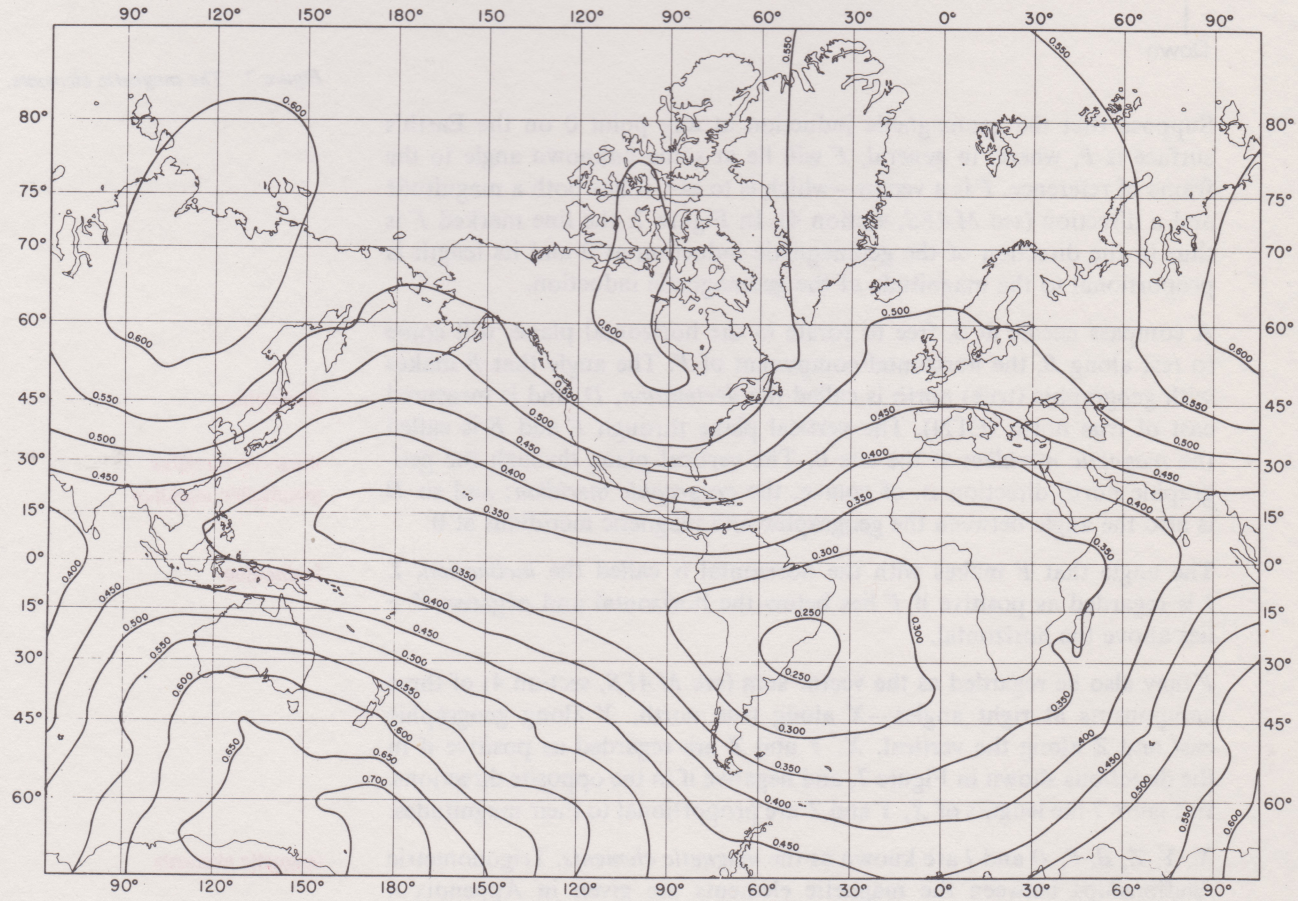


Figure 9 The geomagnetic induction, F, for the year 1955. Units: $10^{-4}T$.

23.3.3 What is the Earth's field like now?

The question we shall try to answer in this section is: what can be said about the Earth's present field from direct observations and analysis of those observations? Later on we shall examine how the geomagnetic field has changed with time, both during the very recent period and during the many millions of years which preceded it; but for the moment we shall concentrate on the present.

The simplest way of illustrating the features of the present field is to combine the measurements from all over the world into a series of magnetic maps, one map for each of the magnetic elements. If the experimental points were simply to be plotted on a world map, all we would see would be a hotch-potch of points which would obscure any regular pattern there might be. Instead, therefore, it is better to plot the magnetic elements as 'contour' lines joining points on the Earth's surface at which a given magnetic element is the same. Such maps are called *isomagnetic charts*. Lines joining the points at which the declination values are equal are called *isogonic lines*, or simply *isogonics*, and thus give rise to an *isogonic chart*. Similarly, lines of equal inclination are called *isoclinics*. Isomagnetic lines for the other elements do not have special names, but the principles behind their construction are the same.

isomagnetic chart

isogonics
isogonic chart
isoclinics

It is not possible to show all seven of the isomagnetic charts here; but to give you an idea of what the Earth's field looks like plotted this way, Figures 8 and 9 show the charts of equal declination, D, and equal geomagnetic induction, F, for the year 1955.

Looking at these maps you will probably conclude that there is little regularity about the geomagnetic field at all. To be sure, there is a pattern of sorts; but what can be deduced from it? Does the geomagnetic field bear any resemblance to the field produced by a magnetic dipole, for example? One way in which we could proceed to test this idea would be to assume that the Earth contains a magnetic dipole at its centre, work out what sort of field this would produce at the Earth's surface and compare this with the observed field. When this is done it is, in fact, possible to show that the geomagnetic field is a dipole field to a first approximation. However, there is a limit to which such a simple model can be taken. To simulate the observed field more accurately a more complex model must be used; and the one normally adopted is not a physical but a mathematical model.

The geomagnetic data from around the world are analysed into complex mathematical 'components', only one of which represents a dipole. What emerges from the analysis is a picture of the Earth's magnetic field which has the following characteristics.

1 All but a few per cent of the geomagnetic field is produced by processes inside the Earth—that is, most of the field is of internal origin, and is often called the *internal field*. The rest of the field we observe at the Earth's surface is of external origin—(the *external field*)—that is, it is produced by effects above the Earth's surface. Most of the external field is probably produced by the motion of charged particles in the upper atmosphere. The external field is comparatively unimportant, and we will be concerned no further with it here. But we shall return to the question of where the main internal field is produced when we consider its origin.

Earth's internal field
Earth's external field

2 The Earth's field is mainly dipolar. This does not necessarily mean that the field is produced by a bar magnet or solenoid in the Earth—in fact, it is not—but only that whatever the origin of the field is, the shape of the field is very similar to that of a solenoid or bar magnet. However, the real processes which produce the dipole field of the Earth are probably extremely complex and difficult to visualize. For this reason it is convenient,

for purposes of representation, to *imagine* a dipole in the Earth. This is known as the *geomagnetic dipole.*

geomagnetic dipole

3 The geomagnetic dipole lies at the centre of the Earth (we therefore say that it is *geocentric*), but does not lie exactly along the rotational axis (we therefore say that it is not an *axial dipole*). It is, in fact, inclined at about 11° to the rotational axis. The points at which the geomagnetic dipole axis cuts the Earth's surface are called the *geomagnetic poles.* The *north geomagnetic pole* is at about 79°N, 70°W; and the *south geomagnetic pole* is at about 79°S, 110°E (you do not need to remember these figures). The arrangement of the geomagnetic dipole is shown in Figure 10. Notice

geocentricity
axial dipole

geomagnetic poles

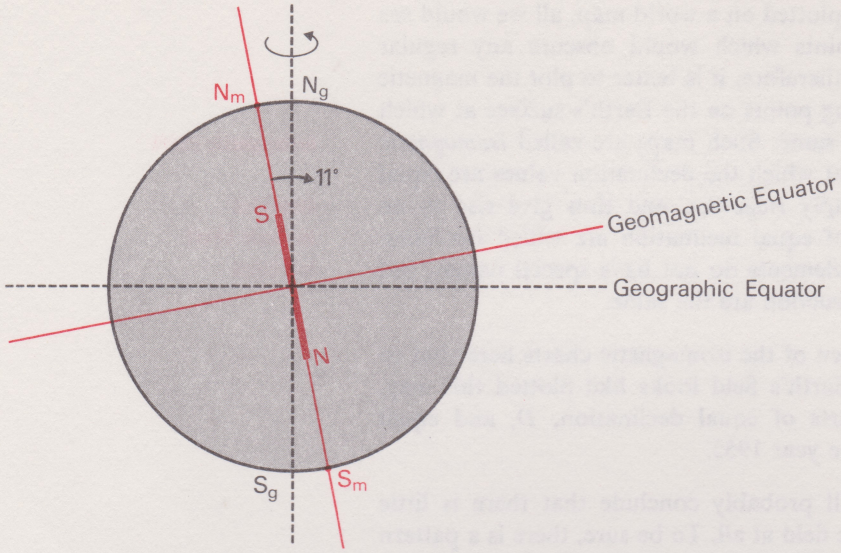


Figure 10 *The geocentric non-axial dipole.*

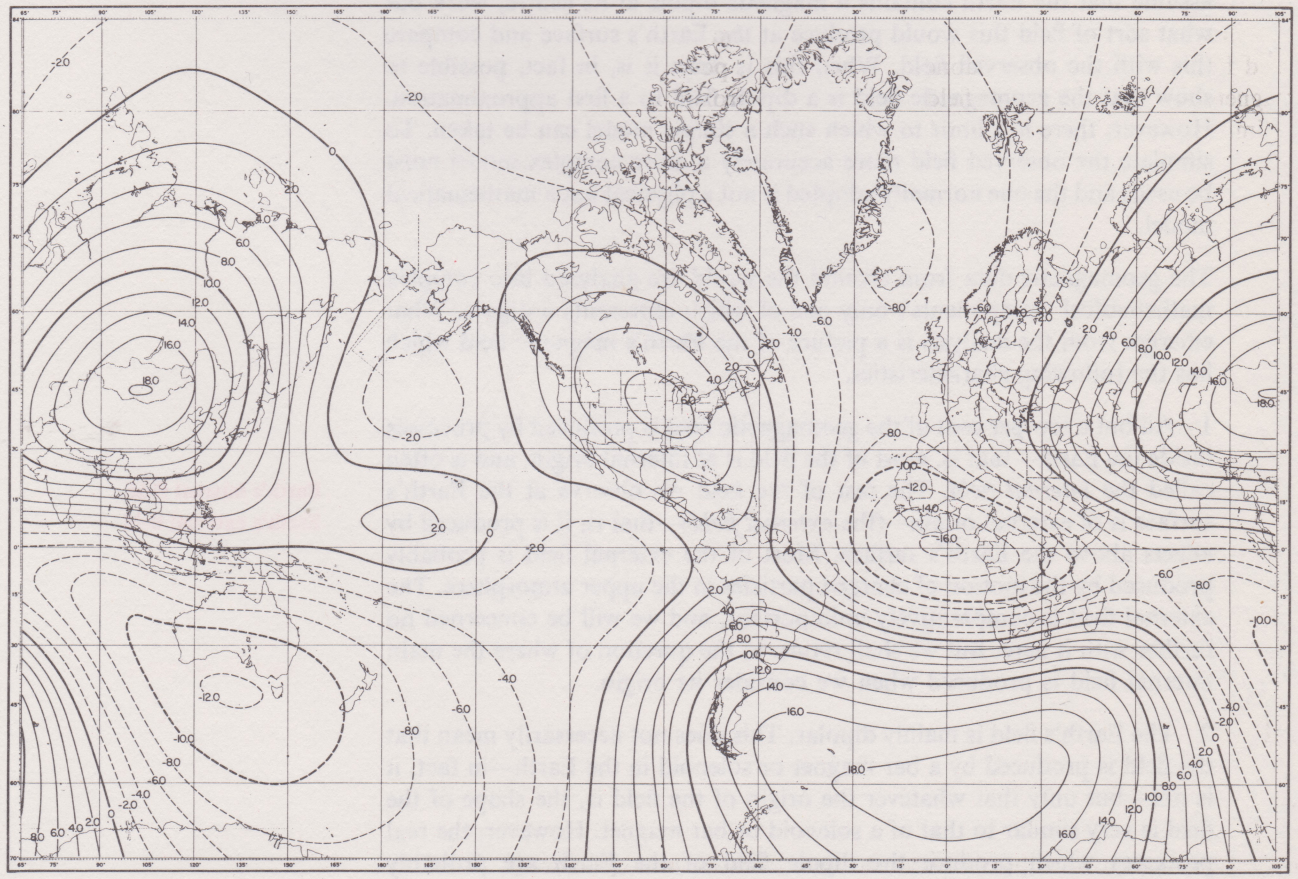


Figure 11 *The* Z *component of the non-dipole field for* 1965. *Units:* $10^{-6}T$.

carefully the *sense* of the geomagnetic dipole. What we actually call the north geomagnetic pole corresponds to the south pole of the geomagnetic dipole itself, and vice versa. You should also realize that the use of the word 'pole' in 'geomagnetic pole' is different from the usage applied to the bar magnet in section 23.2.1.

4 If the geomagnetic dipole were the only component of the Earth's magnetic field, the geomagnetic induction at each geomagnetic pole would be 62×10^{-6}T, and 31×10^{-6}T around the *geomagnetic equator* (see Fig. 10).

geomagnetic equator

5 In fact, the geomagnetic dipole is not the only component present. In addition to the dipole field there is also a non-dipole field which is irregular. It is this field which accounts for most of the irregularities on the isomagnetic charts. The non-dipole field is superimposed on the dipole field; and if the latter is subtracted mathematically from the total field we are left with the pure non-dipole field. The magnetic elements for this field may then be contoured onto a world map just as the magnetic elements of the total field. The Z (vertical) component of the non-dipole field for 1965 is shown in Figure 11.

If you examine Figure 11 carefully you will see that the non-dipole field forms a series of high (induction positive) and low (induction negative) 'centres'. Thus, for example, just off the west coast of Africa there is a low centre which reaches -16×10^{-6}T, whereas over China there is a high centre which reaches $+18 \times 10^{-6}$T. These extremes compare with the dipole field whose induction varies from about 31×10^{-6}T at the equator to 62×10^{-6}T at the poles. You can see, therefore, that in some areas the non-dipole field can be quite a high proportion of the total. On average, however, the non-dipole field is only about 5 per cent of the total.

Have you seen 'centres' of this type before? If so, where?

If you look back at Figures 8 and 9 you will see that the 'centres' are reflected there also. They are not in the same places because we are now looking at the effect of the dipole field as well—but it is clear that the non-dipole field has made its mark.

6 At the north geomagnetic pole the inclination, I, of *the dipole field* is $+90°$, that is, vertically downwards; and at the south geomagnetic pole the dipolar inclination is $-90°$, vertically upwards. However, when the inclination is actually measured at the geomagnetic poles, it is not found to be 90°.

Can you see why?

This is because at the geomagnetic poles there is also a non-zero component of the non-dipole field. The inclination at the geomagnetic poles is the net result of the 90° dipolar inclination and the non-dipole inclination.

However, there are points at which the dipole and non-dipole fields just balance in such a way that the net inclination is vertical. These are called the *magnetic dip poles*. The *north magnetic dip pole* is at about 75° N, 101° W; and the *south magnetic dip pole* is at about 67° S, 143° E. (Again, you are not required to remember these figures.) The dip poles are thus not antipodal. This is because the non-dipole field is irregular and very different in each hemisphere. The non-dipole field bears no regular relationship to either latitude or longitude; and so neither do the points at which the dipole and non-dipole inclinations cancel.

magnetic dip poles

23.3.4 How has the geomagnetic field changed?

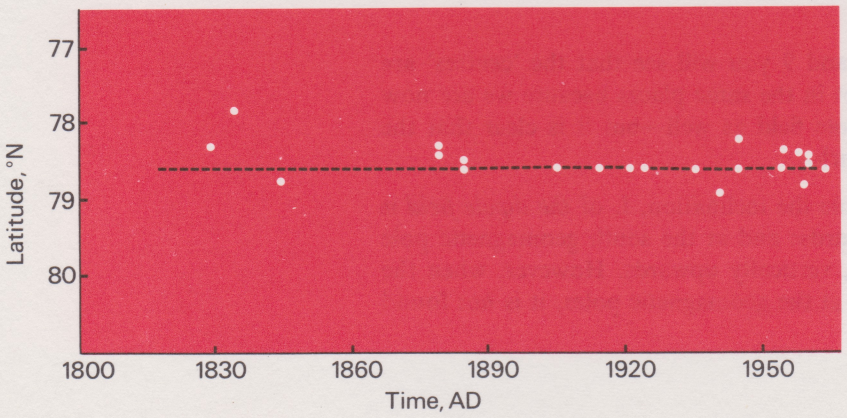
In 1635, Henry Gellibrand presented his discovery that between 1580 and 1634 the declination at London had changed from 11.3° E to 4.1° E. This was the first time that anyone had noticed that the Earth's magnetic field was not static, although one has to admit that the only magnetic elements that had ever been measured up to that time were declination and inclination, and that these early measurements were hardly the ultimate in accuracy. Subsequent observers found, especially after the more systematic measurements were begun early in the nineteenth century, that all the magnetic elements change with time. These changes are known as *secular variations*, where 'secular' as used here merely means 'time'.

secular variations

Since 1838, when Gauss carried out the first mathematical analysis of the geomagnetic field, the field has been under observation almost continuously, and has been the subject of many subsequent analyses. These observations and analyses have enabled geophysicists to plot the changes that have taken place. What we shall do, then, is to summarize, with the aid of diagrams, what has been happening to the Earth's field over the past century or so.

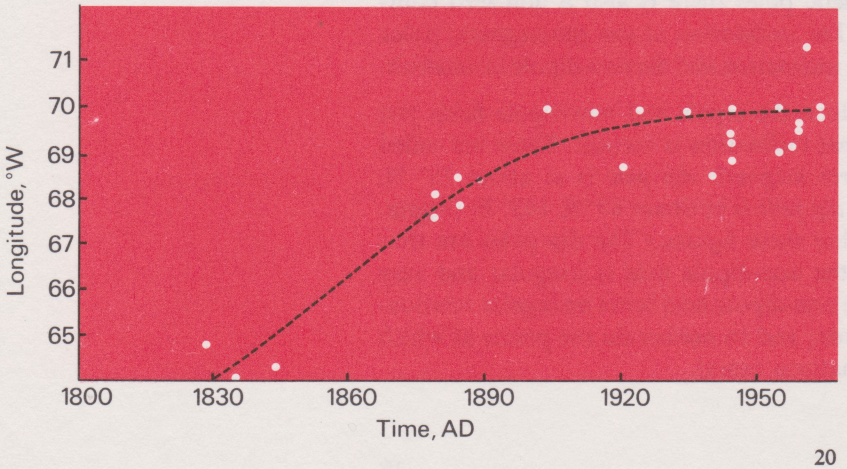
The geomagnetic dipole

Throughout the whole of the period covered by direct observation, the geomagnetic field has been predominantly dipolar; but the axis of the dipole has moved a little. Figure 12 (a) and (b) show, respectively, how the latitude and longitude of the north geomagnetic pole have varied. During this period the latitude has remained the same, and thus the angle between the geographic and dipole axes has remained steady at about 11°. The



(*a*)

Figure 12 *The change in the position of the north geomagnetic pole:* (*a*) *latitude;* (*b*) *longitude.*



(*b*)

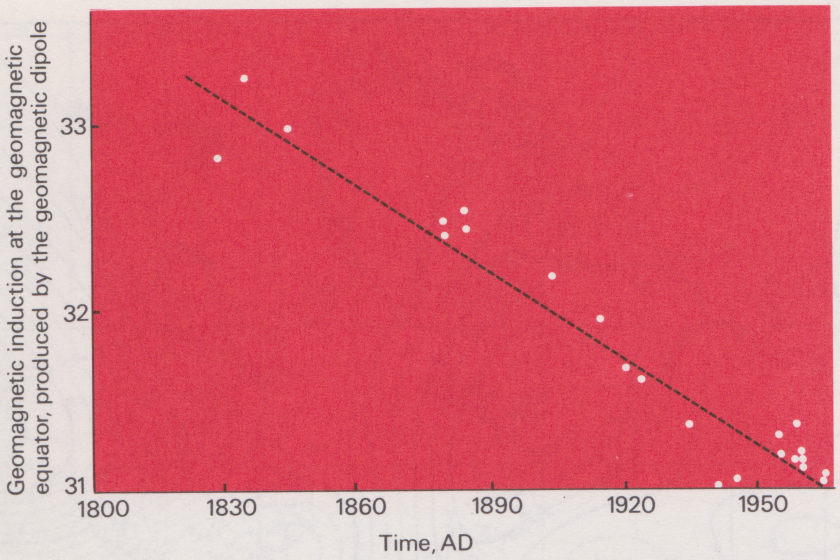


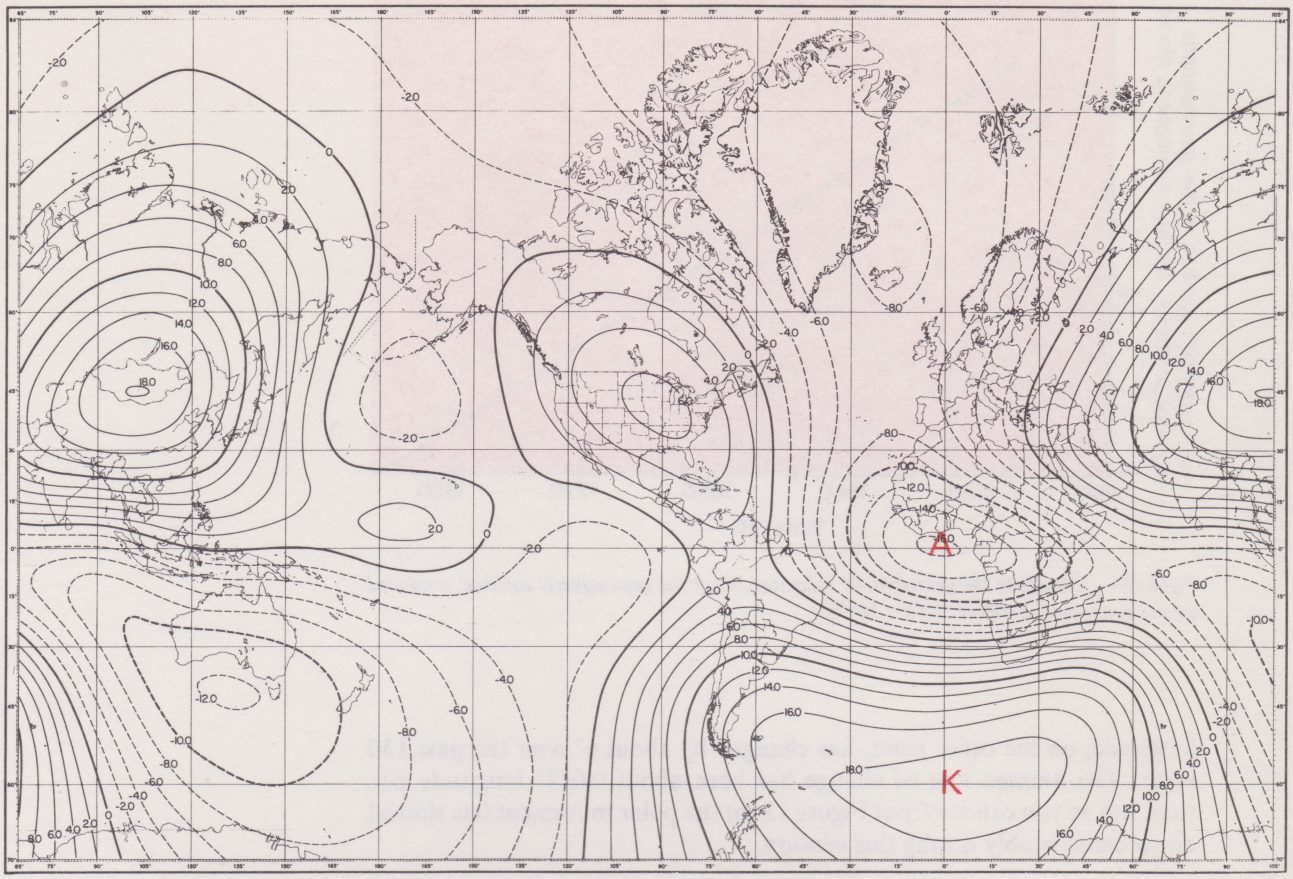
Figure 13 *Change in the geomagnetic induction, F, at the geomagnetic equator, produced by the geomagnetic dipole. Units:* $10^{-6}T$.

longitude, on the other hand, has changed by about 6° over the past 130 years. The *average* rate of change has been about 0.042° longitude per year, but as you can see from Figure 12 (b) the polar movement has slowed down considerably during this century.

Would you deduce from Figures 12 (a) and (b) that the geomagnetic pole moves around the geographic pole at a constant latitude of 79°?

It is important to realize that at this stage we can say *absolutely nothing definite* about the motion of the geomagnetic pole before the nineteenth century. Prior to the period of direct observation it may have been moving as it has done over the past 130 years or so, or it may not. We can, however, say two things. The first is that *if* the pole has been moving in the way described by Figures 12 (a) and (b), it would have taken about 10^4 years to make a complete revolution—but there is no guarantee that it has been so moving. Secondly, we can make a reasonable speculation about the past behaviour of the geomagnetic dipole. Thus it is reasonable to *expect* that the dipole would lie along the Earth's rotational axis because this is the only *unique* axis in the Earth. If you think about it you will see that any axis drawn through the centre of the Earth is no more likely to be the right one than any other—*except* the rotational axis. In other words, all the axes are indistinguishable except the one that passes through the geographic poles. Yet it is clear from observation that over the past 130 years or so the geomagnetic dipole axis has *not* coincided with the rotational axis and thus that the geographic and geomagnetic poles have not been coincident. If our original speculation is to be correct, therefore, we might infer that the geomagnetic pole wanders about so that *averaged over long periods of time* the geomagnetic and geographic poles coincide. We would thus not expect the dipole to have been always inclined at 11° to the rotational axis—though again we have no evidence from direct observation to say otherwise.

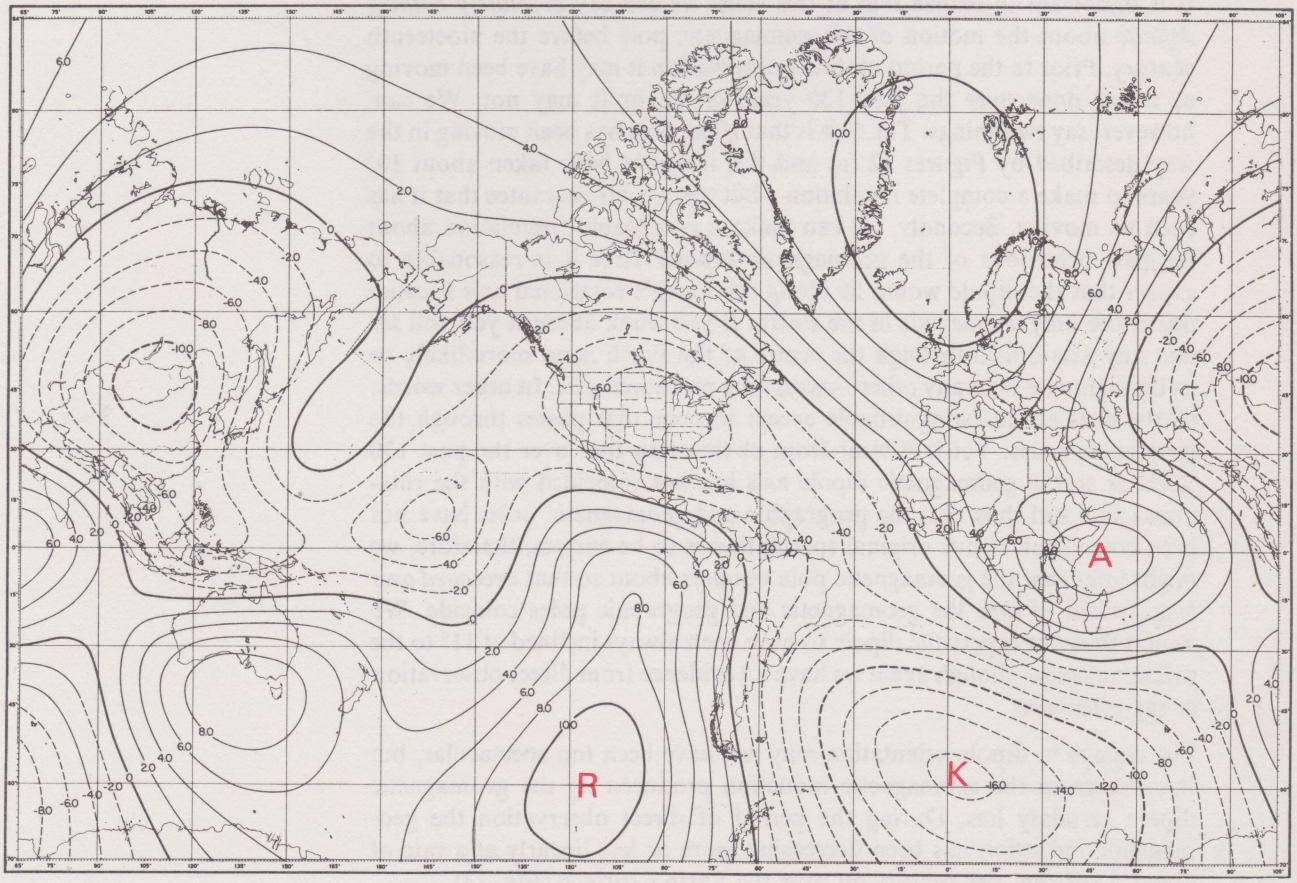
The change in dipole orientation may not have been too spectacular, but the change in the geomagnetic induction produced by the geomagnetic dipole certainly has. During the period of direct observation the geomagnetic induction has been decreasing more or less linearly at a rate of about 5 per cent per century all over the Earth's surface (Fig. 13).



(a)

Figure 14 (*a*) *The* Z *component of the non-dipole field for* 1965. *Units:* $10^{-6}T$. (*b*) *The* Z *component of the non-dipole field for* 1835. *Units:* $10^{-6}T$.

(b)



The non-dipole field

Figures 14 (a) and (b) show, respectively, the Z (vertical) component of the non-dipole fields for 1965 and 1835*. You have met Figure 14 (a) before as Figure 11, but it is repeated here so that you can easily compare the two parts of Figure 14.

Can you spot any essential differences between Figures 14 (a) and (b)?

In a broad way the non-dipole fields for 1835 and 1965 are similar, but there are some important differences. Look first at the 'centre' marked A on each chart. In 1835 its magnitude was greater than 8×10^{-6}T and it lay to the east of Africa. But by 1965 its maximum value had increased to over 16×10^{-6}T and it had moved westward to the west of Africa. Then look at the centre marked K. Between 1835 and 1965 it grew by over 2×10^{-6}T, a somewhat smaller rate than centre A; it again moved westward, but only very slightly; and the whole region between the extreme $Z = 0$ lines expanded somewhat. Then at centre R on the 1835 chart. By 1965 it had completely disappeared. If you have time, take a look at what is happening to some of the other centres.

These particular examples illustrate some very important properties of the non-dipole fields. This field is continuously changing. On average the whole field is drifting westward at a rate of about 0.2° longitude a year. This would seem to imply that if it were to persist long enough it would move right around the world in about 1800 years. In fact, it does not persist in one form for that long. The centres are continuously changing—growing, diminishing, expanding, contracting and disappearing and reappearing—and they do all these things with periods of the order of 10 to 10^3 years. The apparent periodicity of the dipole movement, on the other hand, was, if you recall, of the order of 10^4 years. The non-dipole field is thus changing at a rate which is at least an order of magnitude higher than that of the dipole field.

23.3.5 Indirect measurement of the past geomagnetic field

So now we have seen how the Earth's magnetic field has behaved over the past 130 years or so; but how little we really know! And how many questions are raised by our knowledge of the field over so short a period of time! Has the Earth's field always been dipolar? If so, has it been on average an axial dipole, that is, one aligned with the geographic axis? Or is the axial dipole hypothesis merely a product of wishful thinking—part of Man's attempt to make nature conform to his own intellectual over-simplifications? Has the geomagnetic induction always been decreasing? Are there any long-term variations of the field which could not possibly be determined from direct observation over a mere century or so? For that matter, how long has the Earth even possessed a magnetic field?

Twenty years ago none of these questions could have been answered. Today they can be, at least in part, thanks to a remarkable discovery actually made last century but only developed to any useful degree over the past fifteen years. And that is that many rocks record and preserve the direction and magnitude of the geomagnetic induction at the time they are formed. The study of the magnetization of rocks is called *palaeomagnetism*.

palaeomagnetism

Almost all rocks contain a small quantity (typically a few per cent) of iron compounds. In the types of rock most used for palaeomagnetic work—

* *For reasons which do not concern us here the sign of* Z *has been reversed in Figure* 14 (*b*) (*for* 1835)*—that is,* Z *upward is positive and* Z *downward is negative. Do not forget this point as you compare the charts.*

igneous rocks† (especially basalts†) and sediments† (especially sandstones†) —the important iron minerals are usually magnetite (Fe_3O_4) or hematite (Fe_2O_3), though there is often titanium in place of some of the iron. When a rock is formed, the iron minerals in it become magnetized in the direction of the geomagnetic induction. Furthermore, the strength of the magnetism is proportional to the magnitude of the geomagnetic induction.

However, rocks are extremely weak magnets. A piece of rock having the same dimensions as, say, a toy magnet is usually many hundreds or even thousands of times weaker. Very sensitive instruments are therefore required to measure the magnetic fields rocks produce. On the other hand, the magnetism is extremely stable. Once magnetized, a rock can preserve its magnetism for hundreds of millions of years (compare this with toy magnets, which can be demagnetized very easily). Obviously it is quite impossible to measure the ancient geomagnetic field directly; but all over the world there are rocks of all ages with the ancient fields 'fossilized' into them. And there they lie, waiting to be measured, to divulge the information they have stored for so long.

We shall examine how this information is retrieved in the TV programme for this Unit (23). But in the meantime, let us see how palaeomagnetism answers some of the questions we posed at the beginning of this section.

23.3.6 How old is the geomagnetic field?

Although the Earth is about 4500 Ma (million years) old, the oldest accessible rock is only about 3500 Ma old. Unfortunately, no rocks of this age have been examined palaeomagnetically. The oldest rock examined to date is about 2600 Ma old; and this possessed an original magnetization. The implication, therefore, is that the Earth has possessed a magnetic field for at least 2600 Ma.

23.3.7 Has the geomagnetic field always been mainly dipolar?

Once the declination (D) and inclination (I) of the ancient geomagnetic field at a given site have been obtained from measurement of a rock's principal (magnetic) axis, it is possible to calculate the ancient geomagnetic pole position, or *palaeomagnetic pole position*. The method of doing this is given in Appendix 5 (Black). However, in order to do this we must *assume* the field to be dipolar. Now, you might well ask what use it is to assume the field to be dipolar when we are trying to prove that very point! But this is not quite so silly as it seems. Look at it this way! In dealing with rocks from all over the world, it is quite impossible to test the dipole hypothesis by comparing directions of the ancient field at different sites because, even for a pure dipole field, the direction varies with position on the Earth's surface. The only way in which field directions can be compared is to calculate a parameter which is common to *all* directions. This is conveniently taken to be the principal axis (and hence the poles) of the original global geomagnetic field, irrespective of whether that field was dipolar or something more complex. We then choose to try a dipole field first mainly because the present field is essentially dipolar.

palaeomagnetic pole position

So what would we expect to happen if we are right? If we are right, and the field at a given point in time was dipolar, all rocks of that age, irrespective of their positions on the Earth's surface, should give the same palaeomagnetic pole. However, if we are wrong, and we have calculated pole positions assuming a dipole field when in fact the field was more complex, all rocks of that age will not give a common pole but poles which are scattered all over the place.

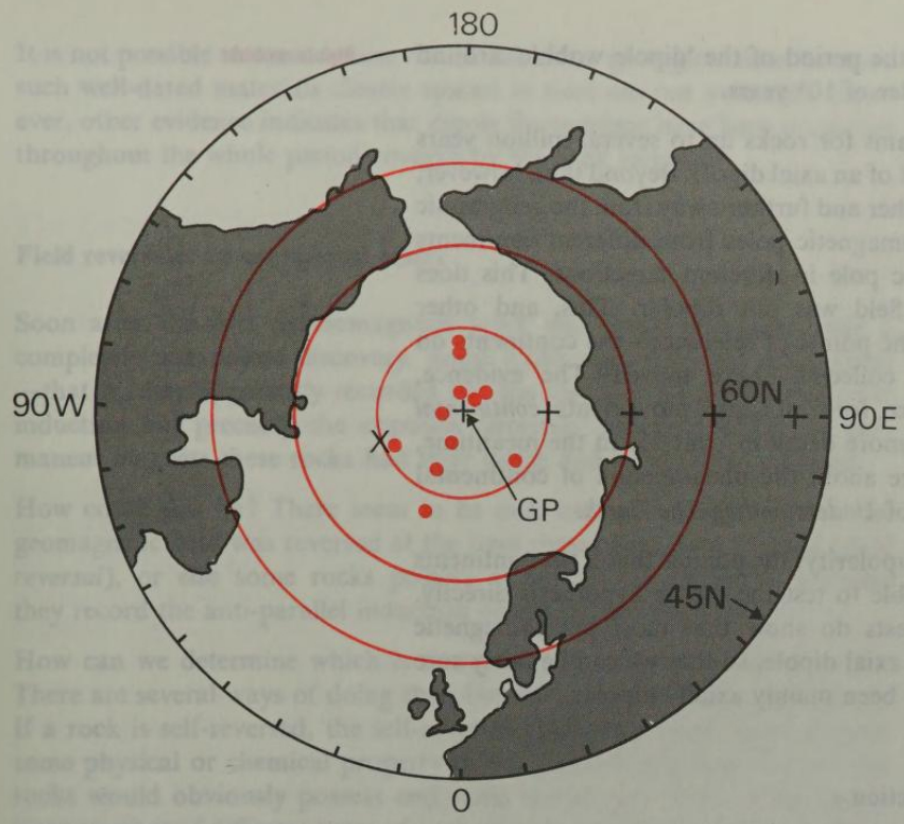


Figure 15 *Palaeomagnetic north poles (●) at different points in time during the past 7000 years. Imagine that you are looking down on the Earth from a point directly above the north geographic pole (GP) which is therefore in the centre of the diagram. The poles are thus plotted exactly as you would see them, assuming they were marked in some way. The cross (×) is the position of the present north geomagnetic pole. Notice that the outer circle represents 45° N latitude; the area between that latitude and the equator, which you would see from your vantage point, has been omitted for clarity.* (Note: *Each of the palaeomagnetic poles shown is an average for many rock samples. In each case, therefore, any scatter there may be from the non-dipole field has been effectively removed.*)

So what happens in practice? If you look at Figure 15 you will see north palaeomagnetic pole positions from rocks up to 7000 years old. Before you go any further read the caption carefully so that you know the positions of the geographic pole and the present geomagnetic pole, and so that you understand what the plot means.

Now look at the palaeomagnetic pole positions. Your first impression may be that they *are* scattered all over the place. In fact, if you look closely you will see that they all lie within about 11° of the geographic pole, which is quite a small scatter when you consider that they could lie anything up to 180° of latitude away. So we can say that over the past 7000 years the geomagnetic field has been mainly dipolar because all the pole positions are very close.

But notice something else! The poles are not scattered around the present geomagnetic pole but around the geographic pole.

What would you deduce from this?

There are several things we can deduce from this. Firstly, the geomagnetic pole has not always been 11° away from the geographic pole, as it is at present, but has wandered around. Secondly, it has wandered around the geographic pole. Thus, on average, it has been an axial dipole. Thirdly, the fact that its maximum deviation from the geographic pole is about 11° suggests that it does not usually wander much further than that. Finally, because, when averaged over a period of 7000 years or so, the

dipole is axial, we can say that the period of the 'dipole wobble' around the geographic pole is of the order of 10^4 years.

dipole wobble

If we were to plot similar diagrams for rocks up to several million years old, we should again see the effect of an axial dipole. Beyond that, however, the palaeomagnetic poles get further and further away from the geographic pole; and, moreover, the palaeomagnetic poles from different continents move away from the geographic pole in different directions. This does not necessarily mean that the field was not dipolar. This, and other evidence strongly suggests that the points of reference—the continents on which the rock samples were collected—have moved. The evidence, including palaeomagnetic evidence, for continental movements (*continental drift*) will be presented in much more detail in Unit 25. In the meantime, you may, if you wish, read more about the phenomenon of continental drift in Chapters 15, 16 and 19 of *Understanding The Earth*.

But to return to the question of dipolarity: the point is that if the continents have moved it becomes impossible to test the dipole hypothesis directly. However, more sophisticated tests do show that most palaeomagnetic directions are *consistent* with an axial dipole, so that we can be fairly sure that the Earth's field has always been mainly axially dipolar.

23.3.8 Changes in the geomagnetic induction

Rocks are not the only things which may be used for palaeomagnetic measurements. Over the past few thousand years, many civilizations in various parts of the world have produced artefacts, such as kilns, which have been baked to high temperatures. These, too, record the direction and magnitude of the geomagnetic induction at the place and time they were baked. Artefacts are particularly useful for investigations of the field over the past few thousand years because in many cases they may be accurately dated by archaeological methods.

Many such materials have been used to determine how the geomagnetic induction from the geomagnetic dipole has varied. All of the data obtained have been used in constructing the curve in Figure 16. This curve shows that over this period of time the geomagnetic induction has been fluctuating with a period of the order of 10^4 years. You will see that the decrease of the induction over the past 130 years or so, also plotted in Figure 16, forms a small part of one fluctuation.

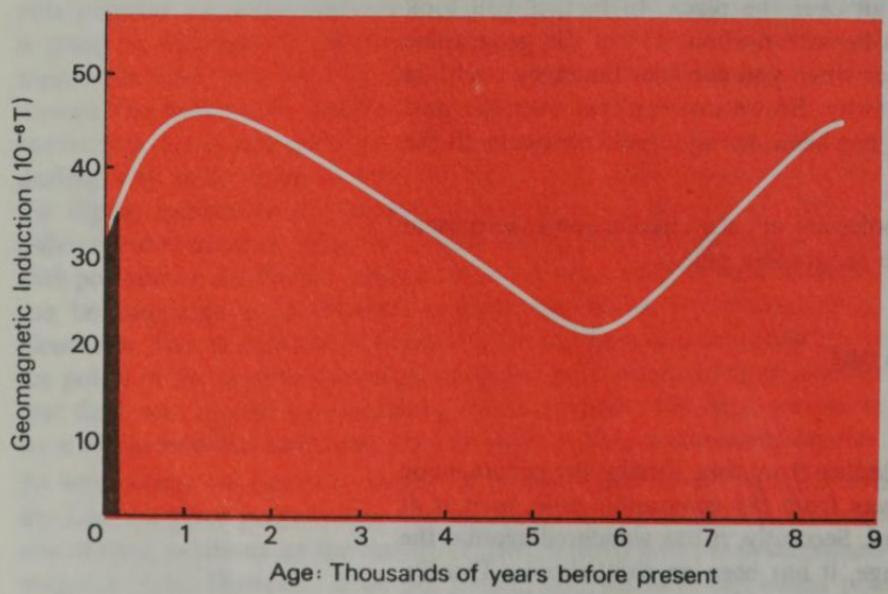


Figure 16 The variation with time of the geomagnetic induction produced at the equator by the geomagnetic dipole. The short line on the left represents the period of direct observation.

It is not possible to extend these results back into geological time, because such well-dated materials closely spaced in time are not available. However, other evidence indicates that dipole fluctuations have been occurring throughout the whole period covered by the rock record.

23.3.9 Field reversals: an unexpected bonus

Soon after the first palaeomagnetic work was done, scientists made a completely unexpected discovery. Some rocks were reversely magnetized —that is, they apparently recorded not the direction of the geomagnetic induction but precisely the opposite direction. In other words, as permanent magnets these rocks had their north and south poles reversed.

How could this be? There seem to be only two possibilities. Either the geomagnetic field was reversed at the time these rocks were formed (*field reversal*), or else some rocks possess some intrinsic property whereby they record the anti-parallel induction direction (*self-reversal*).

field reversal

self-reversal

How can we determine which is correct—field reversal or self-reversal? There are several ways of doing this; but one is of particular importance. If a rock is self-reversed, the self-reversal mechanism must depend upon some physical or chemical property in the rock—a property which some rocks would obviously possess and some would not. Thus, if we take a large number of different types of rock all of the same age, some are likely to be reversed (R) and some not. Non-reversed rocks are termed *normal* (N). If, on the other hand, field reversal is correct, all rocks of one given age will have the same polarity, because at a given point in time the geomagnetic field cannot be both normal and reversed.

normal and reversed rocks

In fact, all rocks of a given age have the same polarity. This was proved in a beautiful piece of work carried out largely by Allan Cox and Richard Doell of the United States Geological Survey over the past decade. What they did was to collect all the young rocks they could, measure their polarities and date them accurately using radiometric dating (see Unit 2 and Chapter 2 of *Understanding The Earth*). Because all rocks of the same age have the same polarity, Cox and Doell were able to build up a well-defined 'polarity/time scale' comprising *epochs*, periods of the order of one million years when the field was predominantly of one polarity, and *events*, shorter periods of opposite polarity within epochs (Fig. 17)*. Unfortunately, it is impossible to extend the polarity/time scale beyond 4.5 Ma ago, because the dating becomes too inaccurate to define the events properly. Thus there is no doubt that reversely magnetized rocks are due to a geomagnetic field which has reversed many times in the past (Fig. 18)*. Although it is not possible to plot a detailed polarity/time scale back beyond 4.5 Ma, reversed rocks exist throughout the whole rock record. Field reversal is thus a fundamental property of the geomagnetic field, and must, like all other properties we have discussed, be incorporated into any valid theory for the origin of the field.

* *Figures* 17 *and* 18 *are on p.* 28.

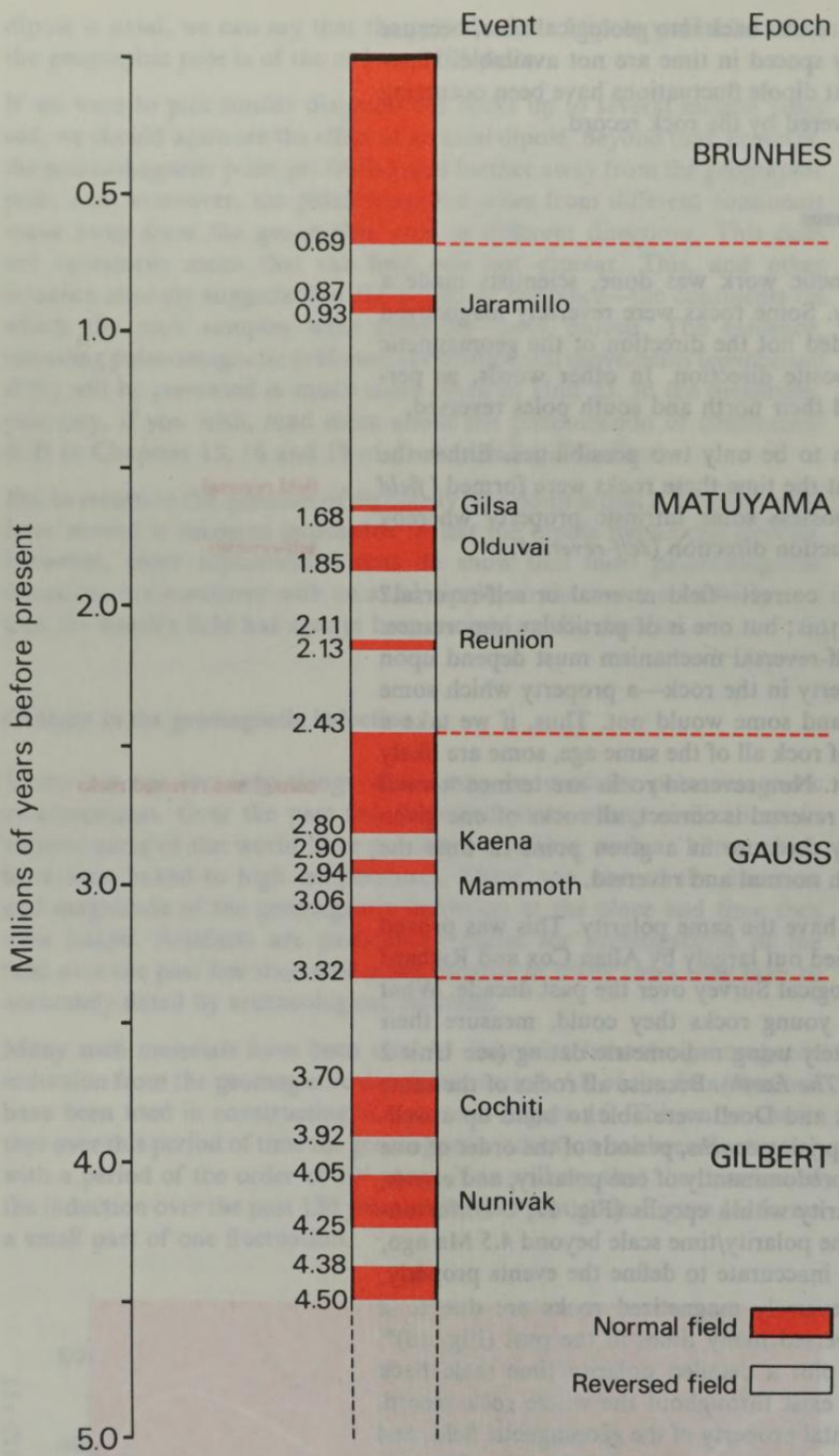


Figure 17 The polarity/time scale for the past 4.5 million years. Notice that both epochs and events have been given names. This scale may not yet be complete; many short events almost certainly remain to be discovered.

(You do not have to remember the details of this diagram.)

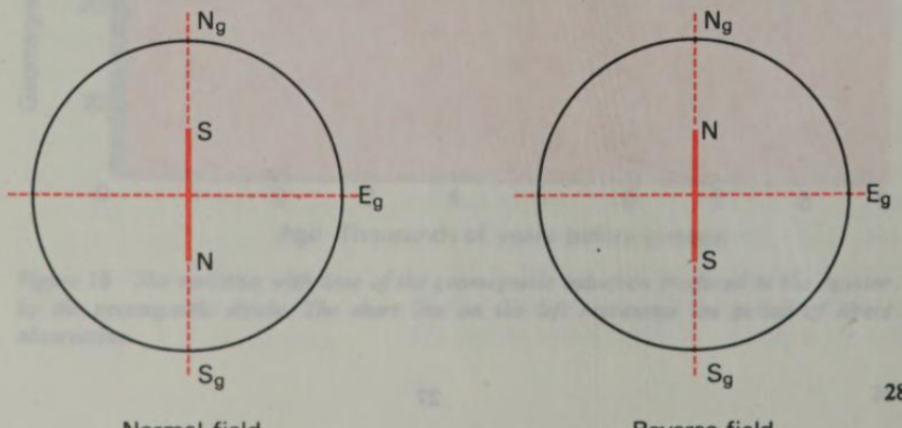


Figure 18 (a) normal field; (b) reverse field.

23.4 The Origin of the Geomagnetic Field

23.4.1 Introduction

Any viable theory for the origin of the Earth's magnetic field must, of course, be able to explain all the known properties of the field, but at the same time must be consistent with what is known about the structure and properties of the Earth from other sources. These two constraints make the search for a satisfactory theory extremely difficult and suggest that such a theory is likely to be complicated. Although there is now a theory which explains the *principle* of geomagnetic field formation fairly satisfactorily, many of the details are still rather vague. Before we look at this, however, it is instructive to first examine briefly two very simple theories, both of which have received a great deal of attention, but which ultimately proved untenable.

23.4.2 Permanent magnetism

The simplest possible explanation for the geomagnetic field is that the Earth is a huge permanent magnet. This is the theory which had the longest life, for it was first proposed by William Gilbert in AD 1600 and had no rival until the late nineteenth century. The great attraction of this idea was the experimental fact that the shape of the magnetic field produced by a spherical, or roughly spherical, uniformly magnetic body is the same as that produced by a magnetic dipole.

Why is this fact important?

Because the geomagnetic field is mainly dipolar, a permanently magnetic Earth would thus explain the principal feature of the observed field. But that is all it explains. There are many serious objections to the theory, any one of which is sufficient to disprove the whole idea. We shall be content with just one fatal flaw.

Each magnetic mineral possesses a characteristic temperature above which its magnetism disappears and it is incapable of retaining magnetization. This temperature is known as the *Curie temperature*, or *Curie point*. For iron and iron minerals the Curie point is usually in the range 500° C to 700° C. Now, the temperature in the Earth increases with depth below the surface at a rate of about 30° C per kilometre. Thus, within a few tens of kilometres of the Earth's surface, no material can possibly be magnetic. If the geomagnetic field is a result of permanent magnetism, that magnetism must reside in a thin outer shell of the Earth; but the materials in this shell are just not magnetic enough to produce a field as strong as that of the Earth.

Curie temperature

23.4.3 Rotation of a massive body

By the middle of this century several other theories had been put forward, but none had proved successful, and so scientists were forced to consider any idea, however unusual it might be. Thus, in 1947, Blackett revived and modified an hypothesis which had first been suggested over twenty

years before—that perhaps magnetism is a fundamental property of a massive rotating body. In other words, he was suggesting that massive rotating bodies might produce magnetic fields *just because they are rotating*.

This theory, too, soon proved unsuccessful. One of the predictions from the theory, as formulated by Blackett, was that the horizontal component (B) of the geomagnetic induction should decrease with depth below the Earth's surface. However, Runcorn made measurements of the geomagnetic induction in mines and found that the horizontal component *increases* with depth. Furthermore, Blackett himself used very sensitive equipment in an attempt to detect directly the magnetic field supposedly produced by rotating gold cylinders. No field could be detected.

23.4.4 The geomagnetic dynamo

geomagnetic dynamo

The above two simple theories were failures; but they share another defect which actually gives a clue to the true source of the geomagnetic field. One of the most important discoveries to emerge from direct observation of the geomagnetic field was that the field is not stationary but is changing rapidly. This is particularly true of the non-dipole field, but even the geomagnetic dipole has changed measurably over the past 130 years or so.

Do you remember how the dipole field has changed during the period of direct observation?

Over this period the geomagnetic induction due to the geomagnetic dipole has been decreasing at the rate of about 5 per cent per century and the geomagnetic poles have moved by about 6° in longitude.

It is clear, then, that any viable theory for the origin of the geomagnetic field must be able to accommodate rapidly changing fields on a global scale. However, both of the simple theories we have mentioned appeal to an origin in the solid part of the Earth. There are no known fluid permanent magnets, for example. Thus, even if these theories were successful in explaining the geomagnetic field as it is now, they would be completely at a loss to explain the changes in the field. For the only way in which rapid field changes could be produced in the solid Earth would be by vast, rapid movements of solid material or extremely large and rapid temperature variations. In either case the consequences would be catastrophic.

So, where in the Earth are rapid changes or movements most likely to occur? The obvious place to look for the source of the geomagnetic field is not in the solid Earth but in that part of the Earth's interior which is fluid.

Which part of the Earth is this?

This means the Earth's outer liquid core. But by what process could a magnetic field be produced by the Earth's core?

Fortunately, there is one possibility which is, in principle, quite easy to understand. You will remember that when we first discussed magnetism itself, we looked at the magnetic interaction between two current-carrying conductors.

How did we 'explain' this interaction?

The current in each conductor reacts with the magnetic field produced by the other to produce a force between the conductors which causes them to move.

Now, it is an experimental fact that this phenomenon also occurs 'in reverse'. If a conductor not carrying a current is moved in a magnetic field, it will have a current produced in it.* This is known as an *induced current*; the current is *induced* in the conductor, but only as long as the conductor is moving. When the conductor stops, the current stops. This is the principle of the *dynamo*.

Let us see what might happen if the dynamo principle is applied to the Earth's liquid core, which is commonly supposed to be a good conductor of electricity—possibly iron. But first it is necessary to make two assumptions: (i) that there is a small non-uniform magnetic field to influence the core initially, and (ii) that the core material is in motion. We shall look at the validity of these assumptions a little later.

It is then possible to visualize the following sequence of events in the core. As the molten conducting material moves in the original magnetic field a current will be induced in it. This is the dynamo action. But a current flowing in a conductor produces a magnetic field, and so the induced current in the moving material will itself produce a magnetic field. This new magnetic field will, in turn, induce a further current in the core material; and this current will then produce a magnetic field. And so on. So here we have not just a simple dynamo, but a dynamo which produces its own magnetic field. This is known as a *self-exciting dynamo*. As long as there was a non-uniform magnetic field present at the beginning to set the process off, and as long as there is a source of energy to keep the core material moving, it is at least conceivable that the core could maintain a magnetic field for ever.

self-exciting dynamo

But does it happen in practice? No one really knows whether motions exist in the Earth's core, let alone what form they might take. If there are motions in the core, however, they are likely to be extremely complex. The problem is intractable in the real situation. Nevertheless, it has been possible to show mathematically in a general way that there do exist motions within a spherical fluid conductor which could cause it to act as a self-exciting dynamo. This does not mean that these particular motions are the ones, or are anything like the ones, which actually occur in the Earth. But at least it has been possible to show that the self-exciting core dynamo is feasible.

Moreover, it is possible to conceive of, and even build, electrical and mechanical devices which illustrate the physical principles of the self-exciting dynamo. The most important of these is discussed by Sir Edward Bullard in Chapter 4 of *Understanding The Earth*. (This is not set reading, but you are, nevertheless, strongly recommended to read it.) Also, in the TV programme for this Unit (23), you will be able to see the world's only working model of a self-exciting dynamo, as built at the University of Newcastle upon Tyne.

Finally, are the two original assumptions likely to be valid for the Earth's core? The initial magnetic field required to start the dynamo does not pose much of a problem. It could, for example, have been a stray field—possibly from the Sun. The source of the energy required to maintain the core motions is unknown, but there are two prime contenders.

* *The current is only produced if the conductor forms part of a complete circuit, and is not produced if the field is uniform (that is, if the field is everywhere constant in magnitude and direction) unless the angle between the conductor and field direction changes.*

1 *Thermal convection currents*

thermal convection currents

If there are heat sources in the core, the temperature there will rise. Heat will be lost by conduction to the mantle; and so even if the heat sources are distributed evenly, the outer parts of the core will be cooler than the deeper parts. Because a decrease in temperature produces an increase in density, there will be denser material towards the outside of the core. The cooler denser material will then sink and the hotter less-dense material deep in the core will rise. In other words, the core material will move around.

The most obvious source of heat to consider is radioactivity. When radioactive isotopes decay (Units 2 and 6) they produce energy which can appear in the form of heat. The three radioactive elements which are important in the Earth, because of their high heat-production, are uranium, thorium and potassium.

2 *Precession*

precession

Owing to gravitational attraction of the Sun and the Moon, the Earth's axis of rotation precesses.

Do you remember what precision is? If not, you should re-read section 22.3.3 of Unit 22.

Because the Earth's core is fluid, it may not exactly follow the precession of the solid part of the Earth. In other words, there could be differential precession between the core and mantle, giving rise to complicated motions in the core.

Thermal convection currents and precession are not mutually exclusive sources for the dynamo energy, however.

23.5 Summary

We began this Unit by considering the fundamental nature of magnetism as a phenomenon arising from moving electric charges. This led naturally to a consideration of the magnetic field, especially that produced by a magnetic dipole. The characteristics of the geomagnetic field were then reviewed, the field throughout the periods of direct observation and the rock record being interpreted as predominantly dipolar but with a non-dipole component. All features of the field were seen to change rapidly with time, which fact led directly to the Earth's liquid core as the only possible field source.

Inevitably, much of the Unit has been concerned with the results of observation of the geomagnetic field. This is because it is far easier to observe the field directly, and even, via palaeomagnetism, to extend these observations back in time for hundreds of millions of years, than it is to formulate a detailed theory for the origin of the field. If, as seems likely, the geomagnetic field is produced by some process in the Earth's core, then the precise details of this process are likely to be complex and not amenable to rapid elucidation.

Appendix 1 (White)

Glossary

ANTIPODAL Two points, or sites, are said to be antipodal when they lie at opposite ends of a diameter of the Earth.

BASALT A fine-grained, dark-coloured igneous rock (q.v.).

HELICAL Spiral (as a corkscrew, for example).

IGNEOUS ROCK A rock formed by solidification from a molten or partially molten state.

SANDSTONE A cemented or compacted sediment (q.v.) comprising mainly quartz grains.

SEDIMENT A loose aggregate of grains deposited from air, water or ice.

Reading List

There is no set reading for this Unit (23); but you are strongly urged to read the following two articles which are particularly relevant to the subject matter of Unit 23.

Understanding the Earth. Chapter 4. The Earth's magnetic field and its origin. Sir Edward Bullard.

R. H. Tucker, A. H. Cook, H. M. Iyer and F. D. Stacey, *Global Geophysics*. Chapter 4. Geomagnetism. F. D. Stacey.

If you wish to read further, the following chapters in *Understanding the Earth* are connected with the subjects covered in Unit 23.

Chapter 2 Measuring geological time. S. Moorbath.
Chapter 5 The Earth's heat and internal temperatures. J. H. Sass.
Chapter 17 The oxidation: polarity paradox. P. J. Smith.
Chapter 18 Polarity reversal and faunal extinction. D. I. Black.

Principles and Applications of Palaeomagnetism. D. H. Tarling. Chapman & Hall, 1971. (£1·75, paper).

Appendix 2

Angular Dependence of Magnetic Force

The induction of the magnetic field produced by a long straight wire (W) was defined in 23.2.2 as the 'would-be force per metre of (test) wire carrying a current of one ampere when placed parallel to W'. Thus in air or vacuum:

$$F = \frac{\mu_0 I}{2\pi r} = B$$

where F is the force on the test wire one metre long and carrying a current of one ampere:

μ_0 is the permeability of a vacuum,
I is the current in W,
r is the separation of W and test wire,
and B is the induction produced by W at the position of the test wire.

However, this expression conceals an important property of the force between two conductors. When the test wire is placed parallel to W, it lies at right-angles to the lines of induction produced by W. If the test wire had not been at right-angles to the induction from W, the force on it would not have been $\mu_0 I/2\pi r$ but lower than that. If the test wire lies at angle θ to B, the force on it is given by:

$$F = \frac{\mu_0 I \sin \theta}{2\pi r}$$

When the test wire lies parallel to B, $\theta = 0$, $\sin \theta = 0$ (see *MAFS*, section 4) and therefore $F = 0$. In this case there is no force on the test wire. But when the test wire lies at right-angles to B, $\theta = 90°$, $\sin \theta = 1$ and therefore $F = \mu_0 I/2\pi r$. In this case F is a maximum because $\sin \theta$ cannot be greater than 1.

The above definition of induction can, therefore, be written in a more general form.

The induction at any position in a *magnetic* field is the maximum would-be force per metre of (test) wire carrying a current of one ampere when placed at that position. In the case of a long straight wire, the would-be force is maximum when the test wire is parallel to the original wire. In order to determine the induction at a point in *any* magnetic field by measuring the force on a test wire, the orientation of the test wire must be altered until the force is at a maximum.

Appendix 3 (Black)

Induction from a Magnetic Dipole

At any point P outside a solenoid and on its principal axis (Fig. 19), the magnetic induction, B, is given by:

$$B = \frac{\mu_0 NIA}{2\pi x^3}$$

where N is the number of turns each of which has a cross-sectional area A, I is the current in the solenoid and x is the distance from P to the centre of the solenoid. And at any point Q outside the solenoid and on an equatorial axis,

$$B = \frac{\mu_0 NIA}{4\pi y^3}$$

where y is the distance from Q to the centre of the solenoid.

In general, at any point R which is distance d from the centre of the solenoid and which lies at an angle α to the principal axis:

$$B = \frac{\mu_0 NIA\ (1+3\cos^2\alpha)^{\frac{1}{2}}}{4\pi d^3}$$

It is easy to see that this general expression reduces to the two special cases when the appropriate values of α are used. Along the principal axis, $\alpha = 0$ and so $\cos\alpha = 1$ and $(1+3\cos^2\alpha)^{\frac{1}{2}} = 2$. In the equatorial plane, $\alpha = 90°$ and so $\cos\alpha = 0$ and $(1+3\cos^2\alpha)^{\frac{1}{2}} = 1$.

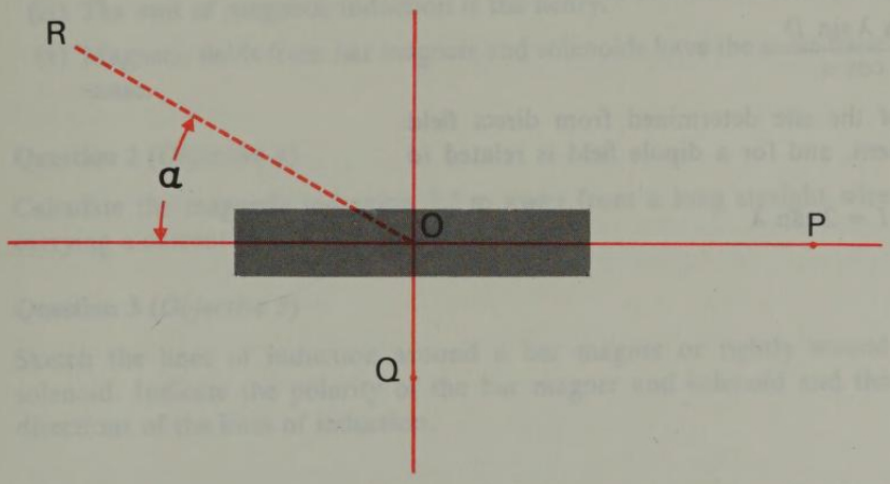


Figure 19 The magnetic induction of a magnetic dipole

The expression for the induction produced by a solenoid contains the product NIA where N, I and A are the three factors and the only three factors which refer to the solenoid itself. If any one of these factors is increased, the induction at any point is also increased. Clearly, then, the factor NIA is in some way a measure of the 'strength' of the solenoid as a magnetic field producer. It is termed the *magnetic moment* or *dipole moment* of the solenoid, and is usually given the symbol μ. (*Note*: This must not be confused with the use of the symbol μ for permeability.)

magnetic moment

Because the bar magnet is also a magnetic dipole, it may also be assigned a magnetic moment to signify its strength. The bar magnet does not, of course, have simple turns nor a current in the sense that a solenoid does, and so its magnetic moment may not be written as a factor such as NIA.

Appendices 4 & 5 (Black)

Relationships Between the Magnetic Elements

The magnetic elements are related by the following simple trigonometric formulae.

$$X = B\cos D \qquad \tan D = \frac{Y}{X} \qquad B^2 = X^2 + Y^2$$

$$Y = B\sin D \qquad\qquad\qquad F^2 = B^2 + Z^2$$

$$B = F\cos I \qquad \tan I = \frac{Z}{B} \qquad\quad = X^2 + Y^2 + Z^2$$

$$Z = F\sin I$$

Calculation of Geomagnetic or Palaeomagnetic Pole Positions

Suppose that we have measured D and I at a site which is at geographic latitude δ and geographic longitude ϕ. Here, D and I may be direct measurements of the field, or may refer to the ancient field recorded by a rock.

Let α and β be the geographic latitude and longitude, respectively, of the geomagnetic or palaeomagnetic pole position. We want to calculate α and β.

Then : (i) $\sin\alpha = \sin\delta\sin\lambda + \cos\delta\cos\lambda\cos D$

(ii) $\sin(\beta - \phi) = \dfrac{\cos\lambda\sin D}{\cos\alpha}$

λ is the *geomagnetic* latitude of the site determined from direct field measurement or rock measurement, and for a dipole field is related to inclination by:

$$\tan I = 2\tan\lambda$$

Self-Assessment Questions

Section 23.2

Question 1 (*Objectives 2, 4, 5*)

Tick to show which of the following statements are true and which are false:

	(*a*) *true*	(*b*) *false*
(i) A compass needle free to rotate in the horizontal plane comes to rest pointing approximately east-west.		
(ii) If the N pole of a magnet is brought close to the S pole of another magnet the force between the poles will be one of attraction.		
(iii) If one of the currents in a pair of long straight current-carrying conductors is switched off, the force between the conductors is halved.		
(iv) A small compass needle placed in a magnetic field comes to rest tangentially to the direction of the magnetic induction.		
(v) If P is a point on the principal axis of a solenoid, lying 2 m from the centre of the solenoid whose length is 0.5 m, and Q is a point on the equatorial axis of the same solenoid, also distant 2 m from the centre, then the magnetic induction at P is twice that at Q.		
(vi) If the currents in a pair of long straight current-carrying conductors are in the same direction, the force between the conductors is one of attraction.		
(vii) Magnetic fields are produced whenever electric charges move with respect to an observer.		
(viii) The permeability of a vacuum, μ_0, is $4\pi 10^{-7}$ H m^{-1}.		
(ix) The unit of magnetic induction is the henry.		
(x) Magnetic fields from bar magnets and solenoids have the same basic cause.		

Question 2 (*Objective 4*)

Calculate the magnetic induction 2.5 m away from a long straight wire carrying a current of 5 A.

Question 3 (*Objective 3*)

Sketch the lines of induction around a bar magnet or tightly wound solenoid. Indicate the polarity of the bar magnet and solenoid and the directions of the lines of induction.

Section 23.3

Question 4 (*Objectives 6, 8*)

Tick to show which of the following statements are true and which are false:

	(*a*) *true*	(*b*) *false*
(i) The frame of reference usually adopted for measurement of the magnetic elements is the Earth's horizontal geographic co-ordinates and the vertical.		
(ii) The inclination of the geomagnetic field at a point on the Earth's surface is the angle between the geomagnetic induction (F) and the vertical.		
(iii) The declination of the geomagnetic field at a point on the Earth's surface is the angle between the geographic and magnetic meridians which pass through that point.		
(iv) A line of equal inclination on a magnetic chart is termed an isogonic.		
(v) An isoclinic is a line on a magnetic chart which joins points of equal inclination.		

Question 5 (*Objective 7*)

What is the simplest scientific observation which indicates that the Earth possesses a magnetic field? Tick the correct answer if it appears in the following list.

(i) The Greeks had discovered lodestone by 600 BC.

(ii) A compass needle mounted horizontally comes to rest everywhere approximately N-S.

(iii) The Chinese had invented the compass by at least the first century AD.

(iv) The geomagnetic field is mainly dipolar.

Question 6 (*Objective 7*)

Arrange the following components of the Earth's magnetic field in the order of their magnitudes by placing 1 (strongest), 2 and 3 alongside the appropriate component.

(i) non-dipole field

(ii) dipole field

(iii) external field

Question 7 (*Objective 9*)

Over the past 130 years or so the non-dipole field of the Earth has been observed to drift westward at an average rate of x and with an average period of the order of y. Tick the space in the following table which indicates the correct values of x and y.

	(a) $y=1$ year	(b) $y=10$ years	(c) $y=10^2$ years	(d) $y=10^3$ years	(e) $y=10^4$ years
(i) $x=0.042°$ longitude per year					
(ii) $x=0.042°$ latitude per year					
(iii) $x=0.5°$ longitude per year					
(iv) $x=0.2$ T per year					
(v) $x=0.2°$ longitude per year					
(vi) $x=0.2°$ latitude per year					

Question 8 (*Objective 7*)

Tick to show which of the following statements are true and which are false:

	(a) *true*	(b) *false*

(i) Most of the magnetic field observed at the Earth's surface is produced by processes outside the Earth.

(ii) An axial dipole is a dipole aligned along the Earth's rotational axis.

(iii) The geomagnetic dipole is axial at the present time.

(iv) The north and south geomagnetic poles are antipodal.

(v) The north geomagnetic pole is closer to the north pole of the geomagnetic dipole than to the south pole of the geomagnetic dipole.

(vi) The geomagnetic induction at the geomagnetic poles pruduced by the geomagnetic dipole is about 0.62×10^{-4} T.

(vii) At the north geomagnetic pole the inclination of the field is $+90°$.

(viii) The north and south magnetic dip poles are antipodal.

Question 9 (*Objective 9*)

That part of the geomagnetic field produced by processes inside the Earth may be divided into two comporents, the dipole field (1) and the non-dipole field (2). Indicate, by inserting 1, 2, or 1 and 2 alongside each item below, to which component(s) the following expressions refer.

(i) Variations with time.

(ii) An average rate of change of about 0.042° longitude per year over the past 130 years or so.

(iii) The westward drift of geomagnetic field 'centres'.

(iv) Growth and decay with periods in the range 10 to 10^3 years.

(v) Constant latitude.

(vi) An induction of 15×10^{-6} T.

(vii) 11° from the rotational axis.

(viii) 0.2° longitude a year.

(ix) A decrease of 5 per cent per century.

(x) A slowing down during this century.

Question 10 (*Objectives 9, 10*)

Tick to show which of the following statements are warranted and which are unwarranted:

	(a) warranted	(b) unwarranted
(i) Direct observation of the Earth's magnetic field indicates that the north geomagnetic pole moves along 79° N latitude, taking about 10^4 years to make a complete revolution around the geographic pole.		
(ii) Because the geomagnetic field is predominantly dipolar it must be produced by a bar magnet at the centre of the Earth.		
(iii) The non-dipole field today looks just as it did about 1800 years ago.		
(iv) The Earth possessed a magnetic field 4000 million years ago.		
(v) Over the past 7000 years the geomagnetic field has been predominantly dipolar and on average that of an axial dipole.		
(vi) The geomagnetic induction has been constant in magnitude over the past few thousand years.		
(vii) The geomagnetic dipole field has reversed many times in the past.		

Section 23.4

Question 11 (*Objective 11*)

The earliest theory for the origin of the geomagnetic field appealed to permanent magnetism in the Earth. Tick the statements below which are relevant to the case against this theory.

(i) Rotating gold cylinders produce no detectable magnetic field.

(ii) Every magnetic mineral possesses a Curie point.

(iii) Rapid large-scale movements of solid material do not occur in the Earth.

(iv) The temperature in the Earth increases with depth below the surface at the rate of about 30° C per kilometre.

(v) Runcorn found that the horizontal component of the geomagnetic induction increases with depth below the Earth's surface.

(vi) The Earth's crust and upper mantle are very weakly magnetic.

(vii) Secular variations of the geomagnetic field are very rapid.

(viii) The shape of the magnetic field produced by a roughly spherical magnetic body is similar to that produced by a magnetic dipole.

Question 12 (*Objective 12*)

The only known viable theory for the origin of the geomagnetic field is that the Earth's fluid core acts as a self-exciting dynamo. Tick the expressions below which relate to the development of this theory.

(i) The Earth's fluid core is a good conductor of electricity.

(ii) A conductor, forming part of a complete circuit, which moves in a magnetic field has a current induced in it.

(iii) The Earth possesses a solid inner core.

(iv) Thermal convection currents in the fluid core.

(v) Earthquake energy in the upper mantle.

(vi) Precession of the Earth.

(vii) Initial magnetic field.

(viii) Permanent magnetism.

Self-Assessment Answers and Comments

The answers to these questions are based on statements of fact given in the text. The numbers in brackets refer to the sub-sections in which the statements occur.

Question 1

(i) False (23.2.1): the compass needle comes to rest pointing roughly north-south. Later in the Unit it becomes clear that this is because the direction of the horizontal component of the geomagnetic induction is approximately north-south.

(ii) True (23.2.1): this is an illustration of the fundamental law of magnetic attraction and repulsion, that like poles repel and unlike poles attract each other.

(iii) False (23.2.2): this is one of the most basic points concerning magnetic fields. The magnetic interaction only takes place when current is flowing in *both* conductors. If one of the currents is switched off the force between the conductors disappears completely.

(iv) True (23.2.2): this arises directly from the way in which lines of induction are defined.

(v) True (23.2.3 and Fig. 5): the dimensions given show that P and Q lie outside the solenoid.

(vi) True (23.2.2): if the currents were in opposite directions the force would be one of repulsion.

(vii) True (23.2.2): remember, however, that this cannot be proved, only inferred.

(viii) True (23.2.2): you will remember that you calculated this value in the problem in the text.

(ix) False (23.2.2): the unit of magnetic induction (B) is the tesla (T), the special name given to Wb m^{-2}. Henry (H) is the special name given to Wb A^{-1}.

(x) True (23.2.3): both fields are produced by the motion of electric charges (the electrons).

Question 2

The equation given in section 23.2.2 for the induction (B) near a long straight current-carrying conductor is

$$B = \frac{\mu_0 I}{2\pi r}$$

where $\mu_0 = 4\pi 10^{-7}$ H m^{-1}, I is the current in the wire and r is the distance from the wire. In this problem, $I = 5$A and $r = 2.5$ m, and so

$$B = \frac{4\pi 10^{-7} \times 5}{2\pi \times 2.5} = 4 \times 10^{-7} \text{ T}$$

Question 3

Your sketch should look just like Figure 6 in the text.

Question 4

The statements given in this question refer to the basic geomagnetic field notation given in section 23.3.2 and the description of isomagnetic charts at the beginning of section 23.3.3. If you have not answered all the questions correctly, you have not heeded the *Study Comment* at the beginning of section 23.3.2. In this case you are strongly advised to re-read section 23.3.2 before proceeding further.

(i) True: in theory, other frames of reference could be chosen. However, the one actually adopted is the simplest; and the geographic co-ordinate system based on the Greenwich 0° longitude is recognized throughout the world.

(ii) False: the inclination is the angle between the geomagnetic induction (F) and the *horizontal*. Again, there is no reason why, in principle, the inclination should not be defined with respect to the vertical. The use of the horizontal is merely a matter of convention.

(iii) True: however, you should note that this is not the *primary* definition of declination. Declination is the angle between the horizontal component (B) of the geomagnetic induction (F) and geographic north. The magnetic meridian is then defined as the plane through B and F. A secondary definition of declination may then be given as in the question.

(iv) False: an isogonic is a line of equal declination.

(v) True: this answer complements that in (iv).

Question 5

The correct answer is (ii). The fact that the compass needle points roughly north-south everywhere at the Earth's surface suggests that the needle is being influenced by a magnetic field in the scale of the Earth itself rather than by a purely local magnetic field (see section 23.3.1). Answer (i) is incorrect because the Greek discovery indicates only that the Earth contains magnetic substances, not that it possesses a magnetic field. Answer (iii) is incorrect because although the Chinese invented the compass they were not aware that the compass direction was influenced by a magnetic field. Even if they had been, their compasses were used over such a small area of the Earth's surface that they would probably not have been able to draw any conclusion about the Earth as a whole. Answer (iv) is also incorrect. The conclusion that the geomagnetic field is mainly dipolar is *derived* from observations of the field—in other words, by this stage the existence of the Earth's magnetic field is not in doubt. Incidentally, to be pedantic, only answer (ii) can be correct because it is the only scientific observation in the list (the question called for a scientific observation). (i) and (iii) are statements of historical fact and (iv) is a conclusion, not an observation.

Question 6

The correct answer is: (i) (2)
(ii) (1)
(iii) (3)

The dipole field is by far the strongest component of the total geomagnetic field (section 23.3.3). On average the non-dipole field amounts to only about 5 per cent of the total and the external field contributes a further few per cent.

Question 7

The correct answer is (v) (d). Because the field drifts weswtard it crosses lines of longitude not latitude. Answers (ii) and (vi) are therefore wrong because they give the drift rate as degrees of latitude per year. Answer (iv) is wrong because T (tesla) per year is a measure of change of magnetic or geomagnetic induction, not a rate of change of field position. The correct drift rate must therefore be (i), (iii) or (v). Which of these three is correct can only be decided by remembering the figure given in section 23.3.4. The average period of the drift (the length of time it would take for the field to drift right around the Earth were it to persist in the same form for so long) is stated in section 23.3.4 but may also be obtained by calculation. There are 360° of longitude around the Earth; and the non-dipole field drifts at the rate of 0.2° longitude a year. The time the field would take to drift right round the Earth is thus 360°/0.2° or about 1800 years. The order of magnitude of this period (that is, the power of ten to which it most closely corresponds) is thus 10^3 years.

Question 8

The answers to the statements in this question are given in section 23.3.3.

(i) False: most of the magnetic field observed at the Earth's surface is produced by processes occurring *inside* the Earth. Only a few per cent of the field is produced externally.

(ii) True: this is simply the definition of the term 'axial'.

(iii) False: at present, the geomagnetic dipole is inclined at about 11° to the rotational axis.

(iv) True: the geomagnetic dipole is geocentric—that is, it lies at the centre of the Earth, or alternatively we can say that the dipole axis passes through the centre of the Earth. The dipole axis cuts the Earth's surface at about 79° N, 70° W (the north geomagnetic pole) and at about 79° S, 110° E (the south geomagnetic pole). These points are antipodal[+].

(v) False: the north geomagnetic pole is, for historical reasons, the name given to the geomagnetic pole which lies closer to the north geographic pole. It is however, the pole towards which the N pole (note the different meaning of 'pole' here) of a compass needle points. But remember that like poles repel and unlike poles attract. The N pole of the compass needle must therefore be attracted to the S pole of the geomagnetic dipole. The so-called north geomagnetic pole is therefore the point at which the *south* end of the dipole axis cuts the Earth's surface. If this is still unclear, look again at the arrangement in Figure 10.

(vi) True: the geomagnetic induction produced by the geomagnetic dipole varies from about 0.31×10^{-4} T at the geomagnetic equator to about 0.62×10^{-4} T at the geomagnetic poles.

(vii) False: at the north geomagnetic pole the inclination of the *dipole* field is +90°. However, at this point the irregular non-dipole field is not zero, and so the resultant inclination differs from +90°.

(viii) False: the magnetic dip poles are the points at which the inclination produced by the dipole and non-dipole fields acting together is either +90° (north magnetic dip pole) or −90° (south magnetic dip pole). These points are not antipodal because the non-dipole field is irregular, being superimposed upon the regular dipole field.

Question 9

This question is based upon section 23.3.4.

(i) 1 and 2: both components vary with time, although the non-dipole field changes much more rapidly.

(ii) 1: this refers to the average rate of change in the longitude of the north geomagnetic pole (and also the south geomagnetic pole, of course).

(iii) 2: the dipole field is regular and therefore does not produce 'centres' as the irregular non-dipole field does. It is the non-dipole field which drifts westwards.

(iv) 2: these are the characteristic periods of the non-dipole field, the 'centres' of which grow and decay.

(v) 1: over the past 130 years or so, the latitude of the north geomagnetic pole (and hence the south geomagnetic pole as well) has remained more or less constant. See Figure 12.

(vi) 2: the induction of the geomagnetic dipole at the Earth's surface varies from about 31×10^{-6} T at the geomagnetic equator to about 62×10^{-6} T at the geomagnetic poles. Any induction lower than 31×10^{-6} T must therefore be due to the non-dipole field. However, since the minimum value of the dipole induction is 31×10^{-6} T, any induction of 15×10^{-6} T *actually measured at the Earth's surface* must be due to a combined non-dipole and dipole field such that the resultant induction is lower than the minimum dipole induction. For example, if the dipole induction at a point on the Earth's surface is 40×10^{-6} T in a given direction and the non-dipole induction at the same point is 25×10^{-6} T in the opposite direction, the net induction at that point will be 15×10^{-6} T. Since dipole and non-dipole fields must act together to produce an induction of less than 31×10^{-6} T, the answer to this question could be regarded as '1 and 2'.

(vii) 1: this is the angle between the rotational axis and the geomagnetic dipole axis over the past 130 years or so.

(viii) 2: this is the average rate of westward drift of the non-dipole field over the past 130 years or so.

(ix) 1: this is the rate of decrease of the geomagnetic induction due to the geomagnetic dipole over the past 130 years or so.

(x) 1: although the average rate of change in the longitude of the geomagnetic poles over the past 130 years or so has been 0.042° per year, the rate was much faster before 1900 than since that time. See Figure 12.

Question 10

The numbers in parentheses refer to the sections relevant to the statements in question.

(i) Unwarranted (23.3.4): direct observation of the geomagnetic field indicates only that over the past 130 years or so the north geomagnetic pole has moved along 79° N latitude at an average rate of 0.042° longitude a year. It tells us nothing at all about what happened to the north geomagnetic pole before about 1840. All that can be said is that *if* the pole has, on average, been moving as it has over the past 130 years or so, it would take about 10^4 years to make a complete

revolution around the geographic pole. However, there is a good theoretical reason for doubting that this has, in fact, occurred.

(ii) Unwarranted (23.3.3): the shape of the geomagnetic field is, to a first approximation, that which would be produced by a bar magnet at the centre of the Earth. But this is a far cry from saying that the field actually is produced by a bar magnet. There is no evidence in favour of this idea and very much against. In many cases, however, it is useful to be able to *represent* the Earth's field source as a bar magnet. But this is just a matter of convenience.

(iii) Unwarranted (23.3.4): the average rate of westward drift of the non-dipole field over the past 130 years or so is 0.2° longitude per year. This would mean that if the non-dipole field were to persist in its present form for 1800 years it would move right around the Earth in that time. But it does not so persist. The features of the non-dipole field are continuously changing, so that the shape of the field today almost certainly bears little resemblance to that of 1800 years ago.

(iv) Unwarranted (23.3.6): the Earth is about 4500 million years old; but the oldest accessible rock is about 3500 million years old and the oldest rock examined palaeomagnetically is about 2600 million years old. It is thus not possible to say whether or not the Earth possessed a magnetic field 4000 million years ago.

(v) Warranted (23.3.7): evidence for this statement comes from the data in Figure 15. You are referred to the text for the interpretation of this diagram.

(vi) Unwarranted (23.3.8): the data plotted in Figure 16 show that, far from remaining constant, the magnitude of the geomagnetic induction has fluctuated widely over the past few thousand years.

(vii) Warranted (23.3.9): the evidence for this is given in the text, especially in Figure 18.

Question 11

The relevant statements are (ii), (iii), (iv) and (vii). For the reasons for the relevancy of these statements you are referred to section 23.4.2 and the beginning of section 23.4.4. Statements (i) and (v) are relevant to disproving the theory that magnetic fields are produced by massive rotating bodies (23.4.3). Statement (viii) is one reason why permanent magnetism was considered in the first place.

Question 12

The relevant expressions are (i), (ii), (iv), (vi) and (vii). Expressions (iii) and (v) are not relevant because, as far as is known, neither the solid inner core nor the mantle play any direct part in the production of the geomagnetic field. Expression (viii) is irrelevant because there can be no permanent magnetism in the fluid core—there are no known fluid permanent magnets and, in any case, the temperature of the core is above the Curie point of any known material. You are referred to section 23.4.4 for an understanding of the relevant expressions.

1 Science: Its Origins, Scales and Limitations
2 Observation and Measurement

3 Mass, Length and Time
4 Forces, Fields and Energy

5 The States of Matter

6 Atoms, Elements and Isotopes: Atomic Structure
7 The Electronic Structure of Atoms

8 The Periodic Table and Chemical Bonding
9 Ions in Solution

10 Covalent Compounds

11, 12 Chemical Reactions

13 Giant Molecules

14 The Chemistry and Structure of the Cell

15, 16 Cell Dynamics and the Control of Cellular Activity

17 The Genetic Code: Growth and Replication
18 Cells and Organisms

19 Evolution by Natural Selection
20 Species and Populations

21 Unity and Diversity

22 The Earth: Its Shape, Internal Structure and Composition

23 The Earth's Magnetic Field

24 Major Features of the Earth's Surface
25 Continental Movement, Sea-floor Spreading and Plate Tectonics

26, 27 Earth History

28 The Wave Nature of Light

29 Quantum Theory
30 Quantum Physics and the Atom

31 The Nucleus of the Atom
32 Elementary Particles

33, 34 Science and Society